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Distributed energy resources systems towards carbon-neutral urban development: A review and application

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Abstract
A new trend in energy systems planning through distributed energy systems has attracted increasing research attention worldwide. Through a comprehensive literature review, this paper presents the latest research and development in the field of distributed energy resource (DER) systems. The review identified five key areas of practice: Relevant concept, supply technology, modeling study, energy systems design, and policy assessment. DER systems offer a wide range of benefits and are linked to sustainable built environments. The paper discusses the applicability of the DER systems in the local energy system of a case study in Stockholm, Sweden. The paper describes a plan and system configurations involved in the search for energy supply options to achieve urban carbon-neutrality in the case study.

Keywords: Carbon-neutral; Distributed energy resource systems; Energy systems; Urban development.

1. Introduction
The building sector consumes large amounts of energy resources, while also producing large quantities of waste and pollution. Buildings usually have a long life span, which means that their impacts on the environment are long and continuing. This makes the building sector particularly interesting in terms of energy utilization, climate change mitigation, and sustainability. According to a report by the Intergovernmental Panel on Climate Change (IPCC), the building sector has greater potential for reducing greenhouse gas (GHG) emissions (estimated at 29 percent by 2030) than any other sector [1]. The International Energy Agency has estimated that current trends in energy demand for buildings will stimulate approximately half of energy supply investments until 2030 in developed countries [2]. In Sweden, the building sector consumes approximately 40 percent of the country’s total energy provision. Residential houses, holiday homes, and commercial premises account for almost 90 percent of the energy use in this sector. Almost 60 percent of the energy use consists of space heating and hot water consumption, while the rest is electricity use divided between operating electricity, household electricity, and electricity for heating [3].
Therefore, the building sector plays a key role in environmental sustainability. Increasing concerns about climate change and resource depletion have resulted in the search for new energy solutions. Local heat and power generation and the use of renewable energy resources are considered to be among the most promising options for providing a cleaner and more secure energy supply. Buildings can be designed to become centers of prosumption; that is, the ability to produce part of what consumes as a product or

service in a sustainable manner [4, 5]. A new trend in energy systems planning is developing toward distributed energy system. An increasing amount of research has addressed distributed energy systems (e.g., [5-9]). Due to distributed energy systems are more efficient, reliable, and environmentally friendly than traditional energy systems.
The literature uses a variety of terminologies, with frequent references to “decentralized energy”, “distributed energy resources”, “distributed energy systems”, “distributed generation”, “on-site energy”, “on-site renewables”, etc. The present paper uses the term “distributed energy resources” (DER), which is often understood as an integrated and decentralized energy system to distinguish it from a traditional centralized system, in which power generation is generated at large, centrally located and centrally controlled plants. DER also refers to small decentralized power generating technologies that can be combined with energy management and energy storage systems, and located close to the point at which the energy is converted to energy services [10]. DER can be either an electric-only resource (solar PV, wind generator, small hydro, etc.), a thermal-only resource (solar thermal), combined heat and power (CHP), or energy storage of both thermal energy and electricity [11].
DER systems offer a promising opportunity for sustainable urban/district development by developing more affordable small-scale energy resource portfolios. DER systems have been considered as possible solutions to energy and environmental challenges [12]. In terms of energy carriers, electricity dominates the medium of exchange and heat also plays an important role. Biofuels and hydrogen are also expected to contribute significantly to the energy exchanges in DER systems. Another advantage is the reduction of primary energy because DER systems are installed close to or even inside the end-users’ facilities, which results in low transmission losses [13]. DER systems are able to provide cost-effective energy services to users. The present paper is restricted to DER systems; tools for analyzing energy, economic, and environmental performance are not included. A comprehensive review of modeling tools for DER systems can be found in [14].
The aim of this paper is to explore how DER systems have been applied to an urban/district development context. This work adds to the existing body of knowledge on the issue of local renewables and DER systems and the application in an on-going urban development project. The specific objectives are to provide a review of the state of the art of DER systems in an urban context, to discuss the latest developments in this field, and to illustrate the adoption of DER systems into a case study. The motivation for this work was supported by the issues related to local renewable energy utilization and to carbon-neutral urban development. The present study differs from the previous ones in that it provides a comprehensive review of DER systems and attempts to classify areas of practice along with the application of DER systems in a case study.
This paper is organized into five sections. Section 1 identifies the contribution of the building sector to global environmental impact and a new trend of urban energy systems planning. Section 2 describes a review methodology and explains methods to support the methodology. The findings and analyses are discussed in Section 3 and an illustrative example of the case study is presented in Section 4. Section 5 summarizes the major findings and future work.

2. Methodology

The works related to the area of DER systems encompass several sectors, techniques, and application domains. The review conducted a broad survey of literature in two stages: (i) analysis of peer-reviewed publications based on the ISI Web of Knowledge database, and (ii) a clustering analysis for identifying the attributes in each cluster.
The term DER is used throughout this paper. However, in order to attract widespread publications in the research database, the first stage of the review was performed by searching the ISI Web of Knowledge database for the terms “distributed energy systems” and “local” in the topic or title fields (Topic=(distributed energy systems) AND Topic=(local)); this produced 942 results. In order to identify a manageable subset of papers, the results were initially filtered by two criteria: (1) research areas and (2) publication had to be in English (98.83 percent of the full data set). The results were then filtered by excluding subject areas deemed irrelevant to the definition, such as astronomy, biology, business economics, forestry, chemistry, health sciences, and water resources. This left 154 studies, representing the document types of proceedings paper (85 studies), article (62), and reviews (12). Taking into account information from ISI Web of Knowledge, Figure 1 shows the distribution of publication by document types. The identified papers primarily represent from 2001 to 2014. The review manually categorized these papers in Mendeley, a reference manager. Seventy-five studies, both theoretical studies and real-

life projects, were found to be relevant to the aim of this review. In the second stage, the set of 75 papers was manually classified using cluster analysis to identify the number of distinct clusters within the data set. The findings suggested five distinct groupings, including relevant concept, supply technology, modeling study, energy systems design, and policy assessment. An analysis was then performed to identify the attributes of each cluster, as shown in Table 1. These attributes provide an indicative assessment of current practices related to DER and urban systems. In addition, the study applied a case study approach to explore the applicability of DER systems for an urban carbon-neutral development project. We conducted a case study to illustrate the adoption of DER technologies for the energy systems design.

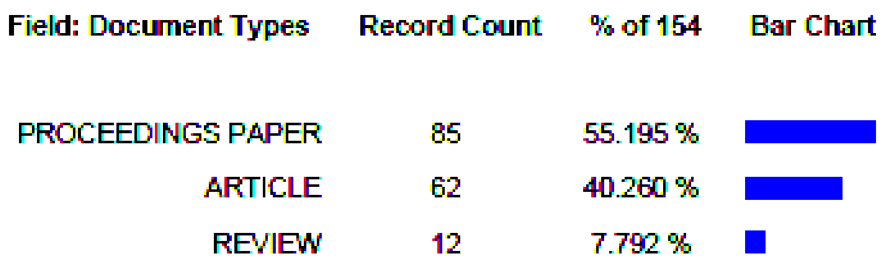

Figure 1. Distribution of publication by document types for 154 ISI Web of Knowledge papers matching the topic = (distributed energy systems) AND topic = (local) and filtered for relevance

3. Results and analysis

There is a lack of consensus about the definition of urban energy systems. Ramaswami et al. [15] and Keirstead et al. [16] suggested three alternative definitions: pure geographic, geographic-plus, and pure consumption. A survey of the relevant publications on scientific journals reveals a wide range of related aspects to DER systems and energy systems planning. In general, most publications consider a set of generation technologies, including renewables, CHP, and trigeneration technologies. Some recent reviews have focused on energy modeling and planning tools (e.g., [12, 16, 17]), while others have dealt with the multi-energy system approach for energy solutions in urban areas (e.g., [18]), and others have addressed technologies for heating, cooling, and power generation (e.g., [9, 19, 20]). Table 1 presents a cluster analysis of the relevant publications conducted in the present study. It was found that the majority of literature in the data set focuses on the modeling study, followed by relevant concept, supply technology, energy systems design, and policy assessment. It should be noted that one paper could be considered in more than one cluster. For example, a paper labeled “modeling study” could also be categorized in “energy systems design”. As papers do not explicitly define, the cluster analysis simultaneously considered multiple characteristics of the papers. The rest of this section examines the attributes of each cluster within the data set.

3.1 Relevant concept

There are 22 studies within the relevant concept cluster. The review found that different research groups and countries use different terms and definitions in relation to DER. According to Ackermann [5], these are “embedded generation” (Anglo-American countries), “dispersed generation” (North American countries), “decentralized generation” (Europe and parts of Asia). The literature also has some relevant emerging concepts, including regional energy clustering [31, 32], integrated energy systems [17, 37], energy hubs [23, 24, 27], micro-grids [26, 29], and the exergy approach [25].

Regional energy clustering is an energy cluster that forms by combining smaller zones to secure sufficient energy balance within the cluster. A specific aspect of the framework involves analyzing the energy surpluses and deficits from defined zones in a region to form energy supply chain clusters with minimum environmental loadings. This concept estimates the energy target and provides the results of energy exchange flows between zones. The integrated energy systems framework, which was launched in 2001 by the US Department of Energy, focuses on integrating distributed generation with thermally activated technologies. The main objectives are to maximize the efficiency of energy use, reduce emissions, and improve power quality and reliability. The energy hubs framework is an integrated system of units that considers multiple energy carriers to be converted, conditioned, and stored. The system components are characterized by using input-output models. Energy hubs consume power at their connected input ports and provide energy services at the output ports. The micro-grid concept focuses on integrating multiple DER technologies into the electricity grid. Micro-grids are local distribution systems that contain generation and load. The exergy approach suggests using the available energy flows by matching the quality of energy requirement to the quality of energy available. The exergy approach is considered to provide new potential for increasing overall energy system efficiency.

Table 1. Cluster analysis of reviewed papers

Cluster	Scale	Reference	n
Relevant concept	Building, Building cluster, City, Community, and District	Ackermann et al. [5]; Pepermans et al. [6]; Herrera [10]; Kumar et al. [11]; Manfren et al. [17]; Bayraktar et al. [21]; Butera [22]; Chicco and Mancarella [23]; Geidl et al. [24]; Gommans [25]; Hatziargyriou et al [26]; Hemmes et al. [27]; Jiayi et al. [28]; Katiraei and Iravani [29]; Kibert and Fard [30]; Lam et al. [31]; Lam et al. [32]; Li et al. [33]; Mangoyana and Smith [34]; Neves and Leal [35]; Wille-Haussmann et al. [36]; and Zaltash et al. [37]	22
Supply technology	Building, City, and District	Akorede et al. [9]; Wolfe [19]; Dong et al. [20]; Gommans [25]; Li et al. [33]; Basak et al. [38]; Bouffard and Kirschen [39]; Klagge and Brocke [40]; Kozman et al. [41]; Ren et al. [42]; and Waseem [43]	11
Modeling study	Building, Building cluster, City, Community, District, and Municipality	Alarcon-Rodriguez et al. [12]; Mehleri et al. [13]; Keirstead et al. [16]; Manfren et al. [17]; Niemi et al. [18]; Bayraktar et al. [21]; Lam et al. [31]; Wille-Haussmann et al. [36]; Ren et al. [42]; Waseem [43]; Adhikari et al. [44]; Ahmed and Zahedi [45]; Baños et al. [46]; Bernotat and Sandberg [47]; Buoro et al. [48]; Calderon and Keirstead [49]; Catrinu [50]; Chen et al. [51]; Chung et al. [52]; Chung and Park [53]; Georgilakis [54]; Hiremath et al. [55]; Liu et al. [56]; Løken [57]; Maribu et al. [58]; Marnay et al. [59]; Medrano et al. [60]; Mendes et al. [61]; Parshall et al. [62]; Pipattanasomporn et al. [63]; Ren et al. [64]; Ren et al. [65]; Soares et al. [66]; Söderman and Pettersson [67]; Weber and Shah [68]; William et al. [69]; Yamaguchi et al. [70]; Yoshizawa [71]; and Zhou et al. [72]	39
Energy systems design	Building, Building cluster Regional, and City	Alanne and Saari [7]; Carley [8]; Mehleri et al. [13]; Manfren et al. [17]; Chicco and Mancarella [23]; Buoro et al. [48]; Chung et al. [52]; Georgilakis [54]; Liu et al. [56]; Marnay et al. [59]; Pipattanasomporn et al. [63]; Ren et al. [64]; Ren et al. [65]; Aki et al. [73]; and Ren et al. [74]	15
Policy assessment	Building, City, District, and Municipality	Neves and Leal [35]; Calderon and Keirstead [49]; Ren et al. [65]; Bourdic and Salat [75]; Bulkeley and Casta [76]; Finney et al. [77]; Longden et al. [78]; Miskinis et al. [79]; Nilsson and Mårtensson [80]; and Pehnt [81]	10

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3.2 Supply technology

Urban energy systems often benefit from promoting innovation and the constraints of existing system configurations. Because DER is often defined on the supply side, this cluster focuses on energy supply technologies. There are 11 studies within this cluster, which generally consider renewable energy technologies and CHP systems. The studies were focused on energy supply technologies, including distributed generation technologies and energy storage technologies [9, 38], CHP systems [20, 25, 41, 42], and decentralized systems [19, 39, 40]. A few of these studies considered demand-side and supply-side technology simultaneously, while some exogenously calculated energy demand. The remaining studies are characterized as calculating supply side parameters related to renewable energy technologies and in some cases including operation.

3.3 Modeling study

The next major cluster is the modeling study, which is the largest group within the data set. The 39 studies within this cluster are comprised of several modeling techniques, including accounting, optimization, and simulation. These studies can be classified as dealing with energy systems and scenario analyses [42, 52, 64, 70, 72], simulation-based optimization [21, 56, 65, 66], energy demand and supply calculation [18, 51, 60, 67], and technology selection [13, 59, 63, 65, 68]. They represent a range of spatial scales from single building [21, 44, 56] to building clusters [13, 47, 48] or districts [51, 70, 71], and whole cities [18, 65]. These publications have relied primarily on the use of optimization techniques such as single and multi-objective optimization methods. Interestingly, the optimization techniques have changed over time. A number of methods for DER systems have been proposed, including genetic algorithms, Tabu search, evolution strategies, artificial neural networks, and particle swarm optimization. This finding is in line with previous work, as stated by Mendes et al. [61]. Another aspect found within this cluster includes tools or modeling software for local energy planning and analysis, such as HOMER (Hybrid Optimization of Multiple Energy Resources), DER-CAM (Distributed Energy Resources Customer Adoption Model), RETScreen, EnergyPLAN, and generic optimization tools (for example, GenOpt and MATLAB).

3.4 Energy systems design

Energy systems design studies typically consider either a building or building clusters, although district scale and specific sites have been found within the data set. There are 15 studies in this cluster, which are often interrelated with modeling study clusters. Research in this cluster typically investigates the pattern of energy services and the combination of equipment and operation to meet energy demand with objective(s) subject to constraints. Most of these studies considered CHP systems and distributed generation. The computational techniques found in this cluster include linear programming [65, 74], mixed-integer linear programming [13,48,56,59,63], multi-objective optimization [73], the econometric model [8], and the multi-criteria method [74]. Chung et al. [52] studied a CHP plant applied to a mixture of buildings in South Korea and proposed five plans for grouping buildings and estimated annual energy demand. For each plan, 10 scenarios for system construction were simulated to identify fuel consumption, electricity purchase, and heat recovery. Decision support systems have also been studied for the selection and system design of renewable energy technologies [54]. An energy systems engineering framework was applied to the optimal design of energy systems with improved energy efficiency and environmental performance in a commercial building [56]. Manfren et al. [17] conducted a review of studies of distributed generation tools and their main features.

3.5 Policy assessment

Notably, the 10 studies of the policy assessment cluster focused on analyzing environmental and economic performance, and how energy performance might be shaped by policy interventions. These studies were conducted at different spatial scales from the individual building level to a city level. These studies used either the computational model or empirical method. Bourdic and Salat [75] provided a useful review of calculation tools, models, and assessment systems for energy consumption and carbon emissions at the district and city levels. Simulation and optimization techniques were found to assess the economic and environmental performance of the DER technologies [65]. A case study of the city of Sheffield, United Kingdom was conducted to assess the environmental and economic impacts of district energy networks [77]. A detailed life cycle assessment has been applied to investigate environment impacts of distributed energy systems [81]. Policy assessment was found in the application of multi-criteria decision-making, which is used for assessing the implications of technology [78].

4. Illustrative example

In order to show the possibility of achieving urban carbon-neutral, the present study examined a planned new urban development area named Albano, which is located in Stockholm, Sweden. Albano is located between KTH Royal Institute of Technology and Stockholm University and is part of the National Urban Park of Stockholm. Albano covers the development of approximately 150,000m^2 of educational and research facilities (100,000m^2) and student and visiting researcher housing (50,000m^2). It is estimated that construction will start in late 2014. Figure 2 shows the plan layout of the Albano project. The overall goal is for the area to serve as a research laboratory for sustainable urban development in which different solutions can be tested. The aim of the project is to achieve a neutral balance in CO2 emissions caused by energy systems. Albano offers an opportunity to build an internationally competitive research environment that is, at the same time, a leading example of sustainable urban development.

Albano will accommodate different building types, including educational and research facilities, housing for students and visiting scholars, and premises for commercial services such as restaurants and cafes. The project has many participants from different research groups from KTH and Stockholm University. Our contribution to the project is to develop a tool for modeling small-scale carbon-neutral energy systems/services for building clusters and urban districts. We aim to provide strategic guidance for project developers for the implementation of sustainable energy systems.

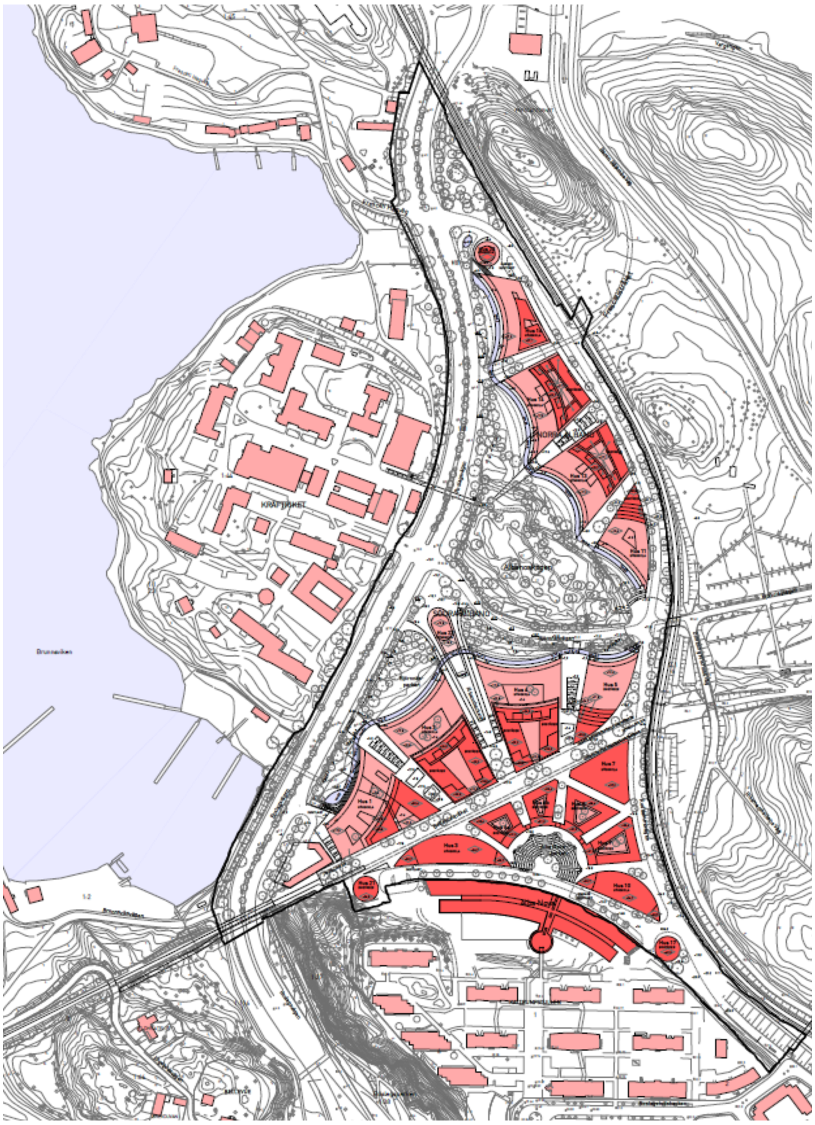

Figure 2. The plan layout of the Albano project. Source: Stockholm City Planning [82]

In a Swedish context, the demand for space heating and hot water represents a large share of total energy demand in building. This paper attempts to explore the adoption of DER technologies and to verify the potential of such technologies. DER systems allow the utilization of renewable resources and have a degree of flexibility to provide energy services to consumers. A preliminary demonstration has been developed through simplified procedures: (i) selection of technologies, and (ii) energy systems design for a pre-determined site. It should be noted that no computational process is performed in the present study and the technical and financial characteristics of energy equipment are not taken into account. The simulation-based optimization will be performed in future work.

Based on the knowledge gained through cluster analysis of reviewed publications, Table 2 summarizes the set of proposed DER technologies and proposed system configurations. Input for the selection of technologies and energy systems design was gathered from a workshop held in Stockholm on 12 June 2013. Workshop discussions were captured by facilitators and invited participants through note-taking on Post-its, flipcharts, and PowerPoint slides. The energy systems have to deliver energy services, such as heating, cooling, hot water, and electricity, to users in order to operate building services such as lighting. The technologies proposed in this paper are utility grid (UG), utility-based hydroelectric (UHE), district heating (DH), photovoltaic (PV) system, wind turbine (WT), solar hot water (SHW), electric heat pump (EHP), ground source heat pump (GHP), biomass CHP, biomass boiler (BB), biogas CHP, absorption refrigerator (AR), thermal storage (TS), battery (BT), and fuel cell (FC). Table 2 presents simplified system configurations of the Albano project. All options are market-available and some, such as district heating and heat pumps, have been widely used in Sweden. In combination with demand-side options such as reducing a building's heat demand through passive design, there is a high probability that Albano will achieve its goal of urban carbon-neutrality.

Table 2. Description of proposed energy system options at Albano

Alternative	Description	System configuration
A1	Conventional system	UG+DH+AR
A2	100% renewable energy system	Biomass CHP+PV+WT+SHW+GHP
A3	Solar, wind, and hydro	UHE+WT+PV+SHW+DH+EHP
A4	Bioenergy system	Biomass CHP+Biogas CHP+AR
A5	Wind energy system	WT+UG+EHP+BT
A6	PV energy storage system	PV+UG+BT+EHP
A7	Energy storage system	UG+PV+WT+BT+TS+GHP+EHP
A8	CHP system	Biomass CHP+UG
A9	Hybrid system	UG+WT+PV+BB+EHP+AR
A10	Fuel cell system	UG+FC+BT+EHP+DH

Previous studies have shown that DER systems have the potential to lead to significant CO_2 emission reductions (see, for example, [9, 12, 65]). However, the optimal technology selection is heavily dependent on the characteristics of the site development. While CHP has high thermodynamic efficiency, which reduces CO_2 emissions and primary energy, the environmental benefits of electrified heating, such as grid-power heat pumps, depend on the carbon intensity of the utility grid from which the electricity is purchased. The energy profiles of a particular site represent the basis for determining the energy system configurations. For example, a site with a steady heat demand that is greater than the electricity demand is likely to be more suited to CHP, whereas an area with electricity demand higher than the heat demand or with a highly intermittent heat demand may be more suited to electrified heating [83]. The question to be addressed in terms of Albano is what the trade-offs are between installing different alternatives (as presented in Table 2) or what the impact is of not using district heating and utility grid.

5. Conclusions

This study has presented certain aspects of DER systems and has reviewed and discussed recent developments in DER systems in an urban context. The papers reviewed herein highlight the benefits of DER systems. A significant contribution of the present paper is its systematic classification that identifies the number of distinct clusters within the data set. The findings from the cluster analysis suggest that modeling study, which involves the use of simulation and optimization, is the largest group of research and development related to DER systems. We also found that optimization is not always about finding the best solution, but is also about exploring alternative solutions. Most of the reviewed studies recognize that the driver for the adoption of DER systems is the environmental benefits. As a result, new modeling techniques have been proposed in recent years. One of the most powerful forms of optimization is multi-objective optimization based on genetic algorithms, which provides a set of solutions that rely on the trade-offs between two or more conflicting objectives. Moreover, a number of case studies have suggested that DER planning is a novel area of research that has attracted increased interest. However, evidence of real application in decision-making support remains limited. Systems engineering is highly valuable as an approach for designing alternative energy futures. As the Albano case illustrates, buildings in the area can be divided into different building clusters, where energy can be exchanged in each building cluster. Each building cluster also allows for the analysis of several issues pertaining to the implementation of DER systems. Several optimal DER systems can be analyzed in comparison to a reference scenario. Finally, findings from this study will serve as inputs for future work on energy systems analyses using a simulation-based optimization technique in which a number of energy system scenarios are evaluated in terms of energy, economic, and environmental performances.

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