

**Prioritising Positive Energy Districts to achieve carbon neutral cities  
Delphi-DANP approach**

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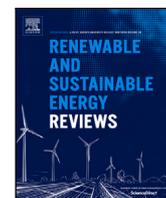
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Original research article

## Prioritising Positive Energy Districts to achieve carbon neutral cities: Delphi-DANP approach

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## ABSTRACT

Identifying districts' potential to become Positive Energy Districts (PED) is challenging but strategic since they are considered critical enablers for cities' carbon neutrality. PEDs are city areas with a positive annual energy balance, achieved primarily through energy efficiency and renewable energy generation while ensuring sufficient energy flexibility. This investigation introduces a methodological framework designed to prioritise and comprehend the potential PED status of diverse districts within a city, drawing upon predetermined criteria and expert insights. The study employs a combination of Decision Making Trial and Evaluation Laboratory (DEMATEL) and Analytic Network Process (ANP) methodologies to scrutinise the city's various districts and the influencing criteria. The method's applicability is tested through to the specific case of Valencia City. The study reveals that the importance of specific criteria in attaining PED varies according to the distinctive attributes of each district. Furthermore, variations emerge based on the perspective and expertise of the contributing experts. The results of this application allowed the selection of the 19 most influential criteria, organised into technical, social, urban, environmental and economic clusters. The two economic criteria (Investment and Grant or projects), one social criterion (Interest or acceptance) and one technical (Potential for retrofitting the buildings), are the most influential overall. The evaluation of the 19 administrative districts of Valencia for each criterion allowed the identification of the districts on the city's outskirts as having the greatest potential to be energy-positive. In conclusion, the proposed methodology aids decision-making in a city's urban energy planning on a district-by-district basis.

## 1. Introduction

Cities consume two-thirds of the world's primary energy demand, and around 75% of energy-related greenhouse gas emissions (GHG) come from cities, making them a key area in the energy transition [1,2]. Cities are being studied for groundbreaking solutions to fight climate change and achieve net-zero goals in line with the Paris Agreement [2]. Cities involve a large concentration of population (56% of the population live in cities) and different types of activity, such as residential, commercial, industrial, and combined residential and commercial areas.

Governments and social agents make decisions that shape cities and the society living in them. Urban planners are currently rethinking the approach to energy planning and taking urban districts as the unit of analysis to address the city as the sum of particular areas [3,4]. The aim is to turn districts into Zero Net Energy Districts (NZEDs) or Positive Energy Districts (PEDs). Amaral et al. [5] argued that the district, as an intermediate urban scale between individual buildings and the city

as a whole, allows a better assessment of the energy performance of buildings, their characteristics, and their urban context, but also better integration of on-site or nearby renewable energy generation and distribution systems. Thus, dividing the city into districts for its planning enables an efficient approach to the energy transition targets [6].

Although the concept of PED has no commonly agreed definition, it emerges from other concepts, such as Zero Energy Buildings [7,8], Positive Energy Blocks [9], and the Net-Zero Energy Districts (NZED) [10, 11], which entail a geographical boundary, interaction state with an energy grid, an energy supply system and a balancing period [12]. PEDs are considered a step beyond NZED. Unlike NZEDs, a PED is not limited to a zero balance of imported energy and greenhouse gas emissions [13]. According to the Joint Programming Initiative (JPI) Urban Europe PED definition [14], the aim is to achieve a positive balance that allows sharing the energy surplus with nearby neighbourhoods and requires interaction and integration between buildings,

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## Nomenclature

### Abbreviations

|         |   |
|---------|---|
| ANP     | Analytic Network Process                        |
| CDI     | Consensus Deviation Index                       |
| DEMATEL | Decision Making Trial and Evaluation Laboratory |
| DANP    | DEMATEL-ANP                                     |
| GHG     | Greenhouse gases                                |
| MCDM    | Multi-Criteria Decision-Making                  |
| PED     | Positive Energy District                        |
| NZED    | Net Zero Energy Districts                       |

### Symbols

|                |   |
|----------------|---|
| $A$            | Direct-relation matrix                    |
| $a_{ij}$       | Values of the direct-relationships matrix |
| $I$            | Identity matrix                           |
| $k$            | Normalisation factor                      |
| $S_{ij}$       | Standard deviation                        |
| $T$            | Total-relation matrix                     |
| $t_{ij}$       | Values of the total-relationships matrix  |
| $X$            | Normalised direct-relation matrix         |
| $\bar{X}_{ij}$ | Average value of item $j$                 |
| $w_{ij}$       | Values of the weighted matrix             |

users, the regional energy system, the mobility sector and information and communication technology systems.

Specific initiatives and influential stakeholders have primarily catalysed the drive toward establishing PEDs. The JPI Urban Europe launched the Strategic Energy Technology Plan to establish 100 PEDs by 2025 [15]. The JPI program aims to involve various stakeholders in its execution, including city authorities, research institutions, industrial partners, energy providers, and civic organisations. The initiative underscores the idea that PEDs not only make substantial contributions towards meeting the goals set by COP21 but also elevate the quality of life within European cities. Furthermore, they enhance Europe's expertise and capacity, positioning it as a prominent global model to emulate. The European Energy Research Alliance Joint Programme on Smart Cities has led the submission of a European Cooperation in Science and Technology action, "PED-EU-NET Positive Energy Districts European Network". This programme promotes open collaboration among relevant stakeholders from various domains and sectors [16]. The International Energy Agency has developed the Energy in Buildings and Communities Programme Annex 83, described as the leading platform for this international scientific debate and research [17]. The aim of Annex 83 is to develop an in-depth framework for PEDs, analysing the technologies, planning tools and decision-making processes. Experience and data for the Annex will be gained from demonstration cases. Through these initiatives, at European and international levels, interest in PEDs has encouraged theoretical and case study research.

PEDs currently undergo a twofold definition process, focusing on how districts are defined and the main parameters that make PEDs possible. Regarding spatial scale, there is uncertainty about the equivalence of administrative divisions in different cities (district, block, community or neighbourhood) [18]. Furthermore, while most studies focus on new districts, PED planning in existing districts is critical to meeting cities' carbon-neutral goals since the building stock in the EU Member States is relatively old. On average, 21.6% of the building stock was built before 1945, 45.4% was built before 1969 and 75.4% before 1990 [19]. Still, historical neighbourhoods present challenging characteristics such as narrow streets and space issues [20], degraded dwellings, low-income families, and gentrification processes due to massive tourism flow [21]. However, transforming all types of

settled districts is essential to meet the European Union's 2050 carbon-neutral ambition [22] and achieve a just energy transition [23]. To address these challenges, different criteria must be involved in designing the most convenient strategies to establish a PED. Each criterion's importance will vary depending on the districts' characteristics and particularities.

Practitioners face a double challenge when deciding which urban districts will become PEDs. First, the lack of data usually makes it difficult to understand how districts perform in energy terms, as these data are technical but also social, environmental and economic. Second, forecasting how districts could perform if chosen as PEDs is also difficult as this transformation implies a socio-technical transition. Moreover, policymakers lack the tools and frameworks to decide and provide a diagnosis to plan actions to transform urban districts into PEDs. As a result of incomplete information, practitioners frequently make incomplete and qualitative diagnoses, with biases appearing due to their background [24].

This study aims to address these challenges by providing a comprehensive identification, definition, parameterisation, and classification of criteria for assessing the potential of urban districts to become PEDs. This holistic approach considers the transformation of urban districts into PEDs as a localised sociotechnical transition. The study introduces a combined Multi-Criteria Decision-Making (MCDM) methodology, based on the Delphi and DEMATEL-Analytic Network Process (DANP), to prioritise and understand the potential of each urban district based on the selected criteria. This methodology enables complex decision processes even when dealing with uncertain and qualitative data. Additionally, the participatory evaluation approach captures diverse urban perspectives on PED pathways and actions, allowing the engagement of various expert profiles, each contributing complementary perspectives. Thus, the proposed methodology allows local authorities to incorporate a holistic approach to assessing the different districts of the city to make better-informed decisions on where to deploy PED policies.

This study demonstrates the applicability of this methodology by applying it to the city of València, Spain. Thanks to the collaboration of 12 experts in energy, urban planning and public policy, it provides a co-designed analysis and prioritisation of the city's different districts. The rest of the paper is organised as follows: Section 2 discusses the current literature around PED, especially the selection and criteria, and Section 3 presents the methodology to assess PED based on different criteria. Section 4 presents the case study of València. Here, the study applies the methodology to obtain results. Section 5 shows the results from the analysis and their implications. Finally, Section 6 concludes by summarising the main findings.

## 2. Positive energy districts and decision making methods

### 2.1. Benefits and potential applications of PEDs

The district, as an intermediate urban scale between the individual buildings and the city as a whole, allows a better assessment of the energy performance of the buildings, their characteristics, and the urban context, but also the better integration of on-site renewable energy generation and distribution systems or in the vicinity [5]. Furthermore, in a review of PED and related projects [25], a higher concentration of projects in mixed-use zones (residential, commercial, office) was observed, concluding that they contribute to more efficient energy use and more opportunities for energy flexibility. An analysis by district makes it possible to address cities' urban and energy complexity in a more simplified way while considering the interactions that take place and the options for improvement.

According to [25], only 7% of PED cases occur in existing (rather than newly built) neighbourhoods. Despite this, they emphasise that the transformation of the existing building stock is a critical component of the urban energy transition, which is the ultimate reason for

PEDs. The analysis of the EU projects MAKING CITY, POcityf, and ATELIER [26] revealed that the transition faced by cities presents many challenges that are not only technological but also economic, social, and governance issues. They see PEDs as staging areas for social, technological, and governance innovation, enhancing participatory processes by bringing together public and private stakeholders and encouraging energy citizenship.

PEDs require systematic facilitation to create local PED ecosystems and develop political constituencies and clusters based on expertise [27]. The PED concept's increasing complexity makes its quick adoption and replication more difficult. The crucial role of engaged key stakeholders, representing the critical mass for every specific PED initiative, is highlighted through lessons learnt from the Smart Cities and Communities lighthouse projects. The challenge is to develop a generic and replicable solution that is adaptive to the contextual characteristics [28]. A systematic understanding of how different contextual factors can affect challenges and aspects in implementing PEDs. A deep understanding of the main criteria and their role in each district will provide a better understanding of the different aspects to be worked on depending on the idiosyncrasies of each district.

## 2.2. PED assessment

Even if they belong to the same city, districts may be very different due to their buildings and facilities [29], evolution over time (conditioned by the inhabitants' income, security matters or geographical differences, for example), the local culture, the relative location in the city, etc. Therefore, there cannot be a one-size-fits-all set of policies to transform different districts. A specific determination of the current energy profile of a PED and the most suitable strategies to transform it into positive energy requires the selection of criteria for its assessment. According to the definition and implications of the PEDs described, the criteria used must consider, among others, energy, urban, territorial, environmental, economic and social aspects. Some recent research focuses on methodological proposals for energy balance calculation [30] or district analysis and modelling [30]. These approaches focus on energy performance, emissions, site opportunities and attributes, the typo-morphology of the built environment, and some amenities (green spaces, collective spaces, connections to the city centre). These aspects are essential for analysing the performance of the districts, but other aspects will also play a role in the pre-evaluation, design or performance phases of PEDs.

Shnapp et al. [31] analysed seven case studies of net-zero energy districts focusing on assessing seven categories (energy, governance, social equity, economic efficiency, conservation and quality of life); for each of these categories, they used different indicators. Angelakoglou et al. [32] stated that 'the projects' success can only be evaluated through specific, tailored Key Performance Indicators (KPI) which need to be defined according to the scope of the specific city interventions and the stakeholders' needs but also provide comparability through established evaluation frameworks and monitoring databases. They also proposed a set of 63 KPIs related to energy, environment, economics, the balance between monitoring feasibility/facilitation and inclusion of the most important and relevant indicators of information and communication technologies, mobility, social aspects, governance and propagation. This list balances monitoring feasibility and inclusion of the most relevant indicators. One of the issues highlighted by the authors is the level of subjectivity involved. These studies focused on performance indicators, which will be used to measure the performance of PEDs. However, to select the district and understand its needs to become a PED, pre-evaluation criteria are needed. The criteria will determine the pre-existing conditions in the district and compare districts with each other. Otherwise, the KPIs, as their name indicates, will be used as indicators to measure performance once the PED is established. Although items listed as KPIs can be used as criteria and the categories established can be useful in a pre-evaluation, such as the one addressed in this study, other items will only be applied in a subsequent phase of the design of a PED for its monitoring.

## 2.3. Multi criteria decision methods

As seen in Sections 2.1 and 2.2, the evaluation of districts for selection as PEDs should consider not only technological but also economic, social, and governance criteria. Furthermore, the advantages that a district may present (for example, low population density) can be disadvantages of other districts (highly populated), which may, in turn, have some other advantages too (e.g. less energy consumption per capita). This multidisciplinary combination of conflicting objectives makes Multicriteria Decision Methods (MCDM) appropriate for assessing PEDs. More information on MCDM can be found at [33]. In particular, this study uses a combination of DEMATEL [34] and ANP [35] (DANP), two widely used MCDM techniques. From a large number of existing MCDM techniques, the DANP technique is selected for this work because it is well-suited to decision-making or evaluation problems with incomplete and sometimes uncertain information, as is the case of Positive Energy Districts [35].

On the one hand, ANP presents its strengths when working with both quantitative and qualitative information. It generalises the decision modelling problem using a cluster network of criteria and alternatives, in this case, the city's districts. The network elements can be related in any possible way, i.e., a network can incorporate feedback and interdependence relationships within and between clusters. In contrast, most other MCDM methods do not support this feature. This provides accurate modelling of complex environments and allows handling the usual interdependence between criteria in decision models, such as prioritising carbon-neutral districts. Paired comparisons between the different elements of the network concerning a third element (triads) are established, and experts elicit judgements according to Saaty's 1–9 ratio scale (1: equally important - 9: One element is extremely more important over the other). More details on the ANP can be found at [36]. This technique has already been widely used in the field of renewable energies and electrification of transport, for example, to assess obstacles to the electrification of urban mobility [37] or obstacles to the participation of renewable energy sources in the electricity market of Colombia [38] as well as for critically analyse generation technologies for hybrid microgrids [39], all of them with interdisciplinary perspectives from technical to social aspects.

The application of ANP can sometimes be problematic, as it is characterised by very complex and time-consuming processes for answering the questionnaires or by the occasional misunderstanding by users of some of the ANP questions stated. In addition, the realisation of the ANP requires a specific structure of the decision-making problem into nodes and clusters. To help structure the problem and decrease some of the problematic features of the ANP application, specific methods, such as the Decision Making Trial and Evaluation Laboratory (DEMATEL) [34] have previously been used. By integrating them into the ANP model, the complexity of the decision-making process is significantly decreased by reducing the number of questions posed to the experts. The combination of DEMATEL and ANP is defined and named in the literature as DANP. The DANP has been used for the selection of renewable energy sources [40] and to examine climate and gender impacts in decarbonisation urban policies [41].

The DEMATEL method [34] has been widely accepted as one of the best methods for modelling influences between components. It is used to structure and analyse the relationships between criteria [42]. It allows the creation of a network of influences between elements (i.e. how the criteria influence each other and the district for the goal of becoming PED) and evaluating them with questions about direct influence, thus avoiding using paired comparisons. A 5-grade scale is used: 0 (no influence between criteria); 1 (low influence between criteria); 2 (medium influence between criteria); 3 (strong influence between criteria); and 4 (very strong influence between criteria). More information about the DEMATEL can be found at [43]. This technique has also been widely used in the field of renewable energies with complex decision models, including different perspectives from technical to social ones, for example, [44,45].

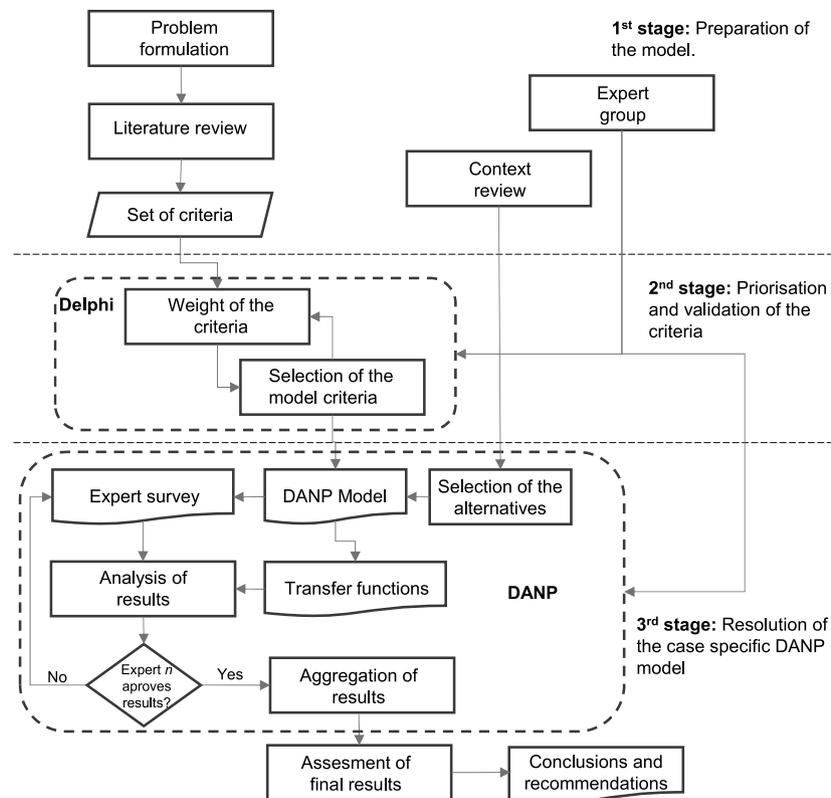


Fig. 1. Summary of the followed methodology.

Recent studies highlight the advantages of combining these two MCDM techniques [46,47]. This combination of methods is approached as follows: the ANP network model of criteria and alternatives is designed for the prioritisation process. Instead of using the 1-0 ANP influence matrix, in this case, the influences between criteria and between criteria and alternatives are assessed with the DEMATEL direct scale. This way, the experts only have to answer one question per cell in the matrix, thus avoiding the high number of paired comparisons required by the pure ANP. Finally, this technique allows consulting different stakeholders to obtain a wider perspective of the problem assessment and solutions.

### 3. Methodology

The methodology used to approach this research is organised in three stages, as presented in Fig. 1. Each major step is described in detail in Sections 3.1 to 3.3.

The first stage, Preparation of the model, is a stage that could be replicated in any study whose objective was to prioritise Energy Districts which wanted to become PEDs. This first stage of the methodology corresponds to the general part and allows its replicability in other cities with the same objective to prioritise PEDs. It is carried out by the facilitators of the prioritisation process, in this case, the authors of this study, and does not require the collaboration of the expert group. In this first stage, a literature review is carried out, and the first list of criteria is thus determined (see Table 1).

In the second stage, Prioritisation and validation of the criteria, the model is refined using the Delphi technique. This requires the collaboration of a panel of experts in the field. This panel of experts will have to be recruited very carefully, taking into account their expertise. The group will work according to the guidelines set by the facilitators. In the first round, they will directly assign importance to each criterion. Then, following the Delphi method [69], the facilitators calculate the averages obtained for each criterion and send them back to the experts

so they can reconsider their judgements. The process is stopped in the second round of judgements, and a new mean is calculated. This last value is used to select the final list of the criteria.

This second stage is only partially extrapolable to other studies, as it depends on the set of experts selected. However, it would probably be since the experts selected have a broad knowledge of carbon-neutral districts in European cities, the final list of weighted criteria can be considered for any European city. Based on the literature review, large European cities' problems are similar overall.

The third stage is the evaluation of the districts: Resolution of the case-specific DANP model for the city of the case study. This is the stage of the context-based methodology, i.e. when replicated, the results presented in this study would not be applicable, and the stage should be carried out specifically for the new case. In this third stage, the local group of experts is reworked. It uses an integrated MCDM approach based on a combination of DEMATEL and ANP (DANP) to determine the ranking of all the districts analysed and the weighting of the criteria. A Multi-criteria analysis is used to evaluate these districts and the criteria, enabling the rank of the districts concerning all the criteria stated in stages 1 and 2.

For this purpose, the experts will answer the DEMATEL questionnaire based on their knowledge. The questionnaire is further divided into two parts. In the first one, in which the influences between districts are analysed, the experts only have to work based on their knowledge. The second part consists of evaluating the performance of each district (alternative) for each criterion. For this purpose, whenever possible, the actual information available from the city council will be used: inhabitants, housing, traffic, public transport, and green areas, among others. The method indicates that transfer functions should be used to transform this information into calculating the district's performance for each criterion. When objective information is unavailable, expert knowledge of the specialists is applied to assess the districts directly based on the agreed Likert scale (see Section 3.3.3).

**Table 1**  
List of pre-selected criteria.

| Technical cluster     |   |  |         |
|-----------------------|---|--|---------|
|                       | Criterion   | Description  | Ref     |
| T1                    | Renewable energy resources  | Renewable resources available in the districts for energy production: sun, wind, geothermal energy, waste, sea, etc.   | [48,49] |
| T2                    | Current renewable generation  | Total annual renewable generation of the district, prior to the PED project.   | [32,50] |
| T3                    | Renewable energy resource potential   | Availability of public or private roofs, gardens or unoccupied plots, underground galleries (for heat exchange), and other elements where renewable energies can be generated.   |         |
| T4                    | Annual electricity consumption per capita in the neighbourhood  | Electricity consumed on average per person in the neighbourhood in a year.   | [31,50] |
| T5                    | Annual thermal consumption of the neighbourhood per capita  | Thermal energy consumed on average per person in the neighbourhood in a year.  |         |
| T6                    | Proportion of energy consumption aligned in the solar timetable, and concentrated in few Supply contracts | More unified and better-focused consumption means more potential. Conversely, the greater the multiplicity of micro-consumption (residential) and the more consumption at night (residential and certain businesses, public buildings, etc.), the worse for the viability of the district.         |         |
| T7                    | Potential for improving the energy efficiency of buildings and activities in the neighbourhood            | Estimation of consumption reduction capacity through the implementation of efficiency measures.  | [15,51] |
| Urban cluster         |   |  |         |
| U1                    | District location   | Location of the district in terms of climate vulnerabilities (higher temperatures, flood risk).  | [52,53] |
| U2                    | Heritage  | Number of heritage listed buildings that may be an impediment to alterations or new installations.   | [32]    |
| U3                    | Average energy quality of buildings   | Related to its energy efficiency, the state of the installations and the energy required for thermal comfort.  | [54,55] |
| U4                    | Area per capita   | The greater the surface per inhabitant, the more space there is for the integration of renewable energy installations or green spaces.   | [5,32]  |
| U5                    | Surface of public buildings and plots   | Roof surface of public buildings or public plots: they are valued as easily available spaces for the implementation of efficiency measures and the installation of RES. Moreover, some of these spaces contribute (social centres, libraries, sports centres) to generate “community” around them. | [56]    |
| U6                    | Total area of green areas   | Area of parks and green spaces that mitigate effects such as anthropogenic heat, improve environmental comfort and reduce visual impact.   | [5]     |
| U7                    | Current developments in mobility  | Safe routes for pedestrians and cyclists. Access to public transport (stops, connections).   | [32,57] |
| U8                    | Vehicle fleet (cars)  | Number of passenger cars per 100 inhabitants. Mobility criterion. The higher the number of vehicles, the more emissions, the greater the difficulty for PED.   | [31]    |
| Environmental cluster |   |  |         |
| A1                    | GHG emissions   | Greenhouse gas emissions to the atmosphere. Total and/or by sector.  | [2,15]  |
| A2                    | Visual impact   | Increased landscape impact of renewable installations.   | [58]    |
| A3                    | Noise pollution   | Current noise level in the neighbourhood. A PED can contribute to noise reduction.   | [32]    |
| A4                    | Average air pollution in the neighbourhood  | A PED will reduce local pollution levels.  | [31,32] |
| Economic cluster      |   |  |         |
| E1                    | Investment  | Estimated investment of the main measures that could be implemented.   | [32]    |
| E2                    | LCOE  | Cost of converting an energy source into electricity. It is measured in €/kWh. It is calculated considering all costs involved in the process over its lifetime. Variation of current LCOE versus after PED.   | [31,59] |
| E3                    | Investment capacity   | District investment capacity for the project.  | [32,60] |
| E4                    | Average energy bill   | Average economic expenditure on energy in the district.  |         |
| E5                    | Grants or projects  | Investments already foreseen in energy or urban planning, in that particular district, in synergic actions with PED. They would reduce the investment initially planned for the PED.   | [31,60] |
| E6                    | Income  | In exchange, they concentrate actions in a single district. Average income per person. Lower income, lower capacity to invest in a PED. The lower the income, the higher the potential interest in participating in a subsidised PED.  | [32,60] |

(continued on next page)

### 3.1. Preparation of the model

The prioritisation model is based on criteria that are obtained from the literature review. This creates a broad initial list of criteria (Table 1) that could also be the starting list for any other European city.

#### 3.1.1. Selection of criteria

A literature review of studies related to PEDs is conducted to obtain the set of criteria. A list of 36 criteria is proposed to assess the potential of districts to become PEDs (see Table 1). The five clusters encompass the main aspects related to the definition of PED and are as follows. The

Table 1 (continued).

|     | Social cluster  |   |         |
|-----|---|---|---------|
| S1  | Interest or acceptance                                    | From residents for the development of a PED project in their district and their participation in it.                              | [60,61] |
| S2  | Cooperative projects                                      | Prior cooperative projects that have created a community in the neighbourhood.  | [62]    |
| S3  | Community organisation                                    | Residents' associations or other associations with active participation and involvement.  | [63]    |
| S4  | Innovation  | Prior innovative projects and platforms for promoting innovation in the district.   | [32]    |
| S5  | Urban ecology and sustainable initiatives                 | Projects, workshops or training. Examples: agroecological markets, proximity markets or urban gardens.                            | [31]    |
| S6  | Vulnerability   | Vulnerability according to GVA data (cartographic viewer: <a href="https://visor.gva.es/visor/">https://visor.gva.es/visor/</a> ) | [64]    |
| S7  | Fuel poverty  | Complex concept mainly related to income, cost of energy and low energy efficiency of homes.                                      | [65,66] |
| S8  | Affordable housing  | Access to affordable housing and the availability of social housing.  | [15,67] |
| S9  | Types of family unit                                      | If there is diversity, it can influence a difference in consumption schedules that would be positive for the PED.                 | [31]    |
| S10 | Population  | Population per district. Disadvantage of too high a population density to achieve PED.  | [31,32] |
| S11 | Usual residence/second homes-tourist rented accommodation | Prioritisation over usual residences to maximise social benefit.  | [68]    |

technical cluster refers to technical aspects related to the development of a PED and, therefore, related to the consumption and generation of energy and the technologies used for it [70,71]. The urban cluster groups together criteria related to the location, the typology of spaces in the neighbourhood, the built-up park, and mobility [72,73]. The environmental cluster refers mainly to the visual impact on the landscape, air quality, noise pollution, and greenhouse gases [70,72]. The economic cluster is focused on the investment capacity and costs of the necessary measures to achieve a PED [25,70]. Finally, the social cluster is related to social aspects linked to the vulnerability of neighbours and their interest and involvement in a PED [28,74].

### 3.1.2. Creation of the panel of experts

During the second phase, one of the most delicate activities of the whole process takes place: the creation of a panel of experts. The number of experts recommended when working with MCDA techniques does not need to be very high; between 10 and 15 is considered sufficient [75]. When working with MCDM techniques in participatory settings, the quality of the participants is more important than the number of participants. Therefore, the facilitators' job should be to recruit these experts correctly, ensuring the required diversity of expertise to cover all the issues of PED and the problem of decarbonisation of European cities.

### 3.1.3. Urban context review

Districts are part of cities, and each city has its particularities. This means that understanding the urban context of each city, as well as its administrative framework, is crucial to studying the potential PEDs in a city. This is especially relevant regarding the data availability, as often the specific, technical and social data needed to perform this study has to correlate to the data provided by the municipality. While smaller units of study might be interesting, these can become unfeasible due to the lack of statistical data or the difficulties among experts in assessing differences among smaller units.

## 3.2. Priorisation and validation of the criteria — Delphi

The experts responsible for the PED agenda are consulted and asked to give their judgement through a Delphi procedure to validate the criteria. The Delphi method is a structured and iterative approach to validate criteria weighting in decision-making processes. It involves a group of experts who provide their input on the relative importance of various criteria. In several feedback and discussion rounds, participants

refine their opinions and converge towards a consensus [36]. This iterative process continues until a clear and stable set of weighted criteria is established. The Delphi method is particularly useful when dealing with complex, uncertain, or contentious decision-making situations, as it allows for the aggregation of diverse expert opinions while minimising bias and promoting a systematic validation of criteria weightings.

In the first round of the questionnaires, experts have to assign a degree of importance to each criterion concerning the general goal of prioritising the most feasible districts to become PED. In the second round, they adjust their perspectives to attain more consistency. A 0 to 4 scale has been used to make these judgements: 0 (no influence), 1 (low influence), 2 (medium influence), 3 (strong influence), and 4 (very strong influence). The same process as for DEMATEL is used for consistency and ease of use for experts. In the study, a Consensus Deviation Index (CDI) is adopted to indicate the degree of expert consensus. The CDI is expressed as follows:

$$CDI = \frac{S_{ij}}{\bar{X}_{ij}} \quad (1)$$

where,  $\bar{X}_{ij}$  represents the average value of item  $j$  and  $S_{ij}$  is the standard deviation. The larger the CDI is, the weaker the expert consensus is. In this study, a threshold of  $CDI = 0.2$  has been used.

## 3.3. Resolution of the DANP model

### 3.3.1. DANP model

In the third stage, and once the criteria have been agreed upon, the DANP method is applied in five steps.

**Step 1:** Generating the direct-relation matrix  $A$ . First, measuring the relationship between criteria and the alternatives requires that the comparison scale is designed in a 0–4 scale, as stated in Section 2.3:

Experts make pairwise comparisons of the influence between criteria and between criteria and alternatives. Then, the initial data is obtained as the direct-relation matrix. The  $A$  matrix is a  $n \times n$  matrix in which  $a_{ij}$  denotes the degree to which the element (criterion or alternative)  $i$  affects the element  $j$ .

Regarding the alternatives (the districts to evaluate), some previously agreed transfer functions might already exist. The transfer functions facilitate an understanding of district behaviour with respect to certain criteria, eliminating the need for expert consultation. In those cases, these transfer functions are parametrised and transformed into the DEMATEL 0–4 scale and used to obtain the direct-relation matrix  $A$ . This will be the case for those quantitative criteria for which data is available for all districts.

**Step 2:** Normalising the direct-relation matrix. On the base of the direct-relation matrix  $A$ , the normalised direct-relation matrix  $X$  can be obtained through equations:

$$X = k \times A \quad (2)$$

$$k = \frac{1}{\max_{1 \leq i \leq N} \sum_{j=1}^n a_{ij}} \quad (3)$$

where,  $a_{ij}$ : values of the direct relationships matrix.

**Step 3:** Attaining the total-relation matrix:  $T$  can be obtained by using (Eq. (4)), in which the  $I$  is denoted as the identity matrix.

$$T = X(I - X)^{-1} \quad (4)$$

**Step 4:** Normalising each column of the  $T$  matrix (unweighted) by its sum to obtain the weighted supermatrix.

$$w_{ij} = \frac{t_{ij}}{\sum_{i=1}^n t_{ij}} \quad (5)$$

where,  $w_{ij}$ : values of the weighted supermatrix and  $t_{ij}$ : values of the total-relation matrix.

**Step 5:** Calculating the limit matrix. In this step, the weighted matrix is multiplied by itself until all of its columns become equal, i.e. the values converge, and the process ends. This way, each element's individual influences on the network's other elements are obtained from this limit supermatrix. The values of the criteria and alternatives are extracted from the vector of the limit supermatrix and normalised by the sum to obtain their final weights or importance. After obtaining the individual evaluation results of DANP, each expert validates her/his own results. If the results are unsatisfactory, she/he revises the evaluation round of the pairwise comparisons to ensure that the results agree with her/his knowledge and overall assessment. This second round relates mainly to experts not being familiar with the methodology, and it is a way to check that their initial thoughts are translated into the results.

The values of these criteria are extracted from the limit supermatrix vector and normalised by the sum to obtain the final weights of the decision criteria. This method obtains the ranking of the criteria, thereby enabling an understanding of the decision profile of the experts.

### 3.3.2. Expert weighting of the criteria and districts

For the weighting of the criteria, experts are asked to conduct pairwise comparisons between criteria. For that, a structured questionnaire was used to provide their opinions on pairwise comparisons. Each expert received one questionnaire and was asked to assess the influences among all the network elements by using a numerical or linguistic scale.

Once the questionnaires of all experts have been gathered and following the DANP procedure explained in Section 3.3.1, the weights of the criteria are calculated. The information from the individual questionnaires can also be aggregated employing the geometric mean to obtain the results of the different subgroups of experts or the global group.

### 3.3.3. Transfer functions to evaluate of districts

Step 1 of the DANP undergoes slight modifications to work on the district assessments. When quantitative data for all the districts (alternatives) are unavailable, the experts will evaluate them directly. However, when quantitative data for all the districts are available, facilitators use transfer functions to generate the direct relationship matrix and to take advantage of the actual data. For this purpose, the methodology transforms those available measures to a DEMATEL 0–4 influence scale using transformation functions. Each transformation function was defined by the authors (procedure facilitators) and agreed upon by the panel of experts. Therefore, some influences of alternatives on criteria had to be qualitatively assessed by the experts with the DEMATEL scale. The transformation functions serve to calculate influences based on quantitative data and are translated to the DEMATEL scale.

### 3.3.4. Assessment of final results

To obtain the district's final prioritisation, the values of these alternatives are extracted from the limit supermatrix vector and normalised by the sum, thus obtaining the districts' ranking and enabling the identification of the most appropriate ones.

## 4. Case study

### 4.1. València

Valencia is a city situated on the eastern coast of Spain, along the Turia River, on the Iberian Peninsula's eastern seaboard, facing the Gulf of Valencia on the Mediterranean Sea. It ranks as Spain's third most populous city and metropolitan area, boasting a population of 789,744 residents within a surface area of 134.65 km<sup>2</sup>. The city's historic centre, spanning approximately 169 hectares, is one of Spain's largest.

Valencia experiences a hot-summer Mediterranean climate characterised by mild winters and hot, dry summers, with an average annual temperature of 18.4 °C. January registers the coldest temperatures, averaging maximums of 16–17 °C and minimums of 7–8 °C. Conversely, August is the warmest month, featuring average maximums of 30–31 °C and minimums of 21–23 °C, accompanied by moderately high relative humidity. The daily temperature range remains narrow due to maritime influences, hovering around 9 °C on average. Additionally, the annual temperature range is limited to 9–10 °C due to the impact of the sea. Valencia's average annual humidity, influenced by the sea, remains relatively high at around 65%, with slight fluctuations throughout the year. Annual rainfall ranges between 450 and 500 mm, with summer lows and autumn peaks, particularly in September and October, linked to heavy rainfall episodes associated with low-pressure cut-off systems at high altitudes.

Valencia's economy leans heavily towards the service sector, employing nearly 84% of the working population, although a significant industrial base persists, with 8.5% of the workforce engaged in industrial activities. Agricultural pursuits, while of minor economic importance, still occur in the municipality, involving only 1.9% of the working population and 3973 hectares primarily dedicated to orchards and citrus groves. In terms of energy consumption, excluding mobility, the total annual electricity consumption of the city in 2019 was 2,548,179 MWh, and the total natural gas consumption was 239,467 MWh. Other minor energy sources included butane or propane. More than half of electricity consumption, 56%, was in the commercial sector and 40% in the residential sector, while 62% of natural gas consumption was in the residential sector, 23% in the industrial sector and 15% in the commercial sector.

The Valencia 2030 Urban Strategy, approved in September 2022, outlines a comprehensive roadmap for developing a more sustainable, healthy, shared, prosperous, entrepreneurial, creative, and Mediterranean city. Integrating Urban Agenda principles with mission-oriented innovation policies, this approach combines urban and innovation policies to expedite urban transformations. The strategic framework comprises 12 strategic lines and 48 goals aligned with the Valencia Climate Mission, leading to Valencia's selection by the European Commission to participate in the cities' mission to deliver 100 climate-neutral and smart cities by 2030. That way, València was selected by the European Commission to participate in the cities mission that is expected to deliver 100 climate-neutral and smart cities by 2030. Particularly, it is one of the ten first European cities that have been granted with the Climate Label with the approval of its Climate City Contract in September 2023 by the European Commission. The Action Plan of the Valencia 2030 Urban Strategy and the Climate Mission include a program dedicated to Energy Transitions, with one of its Action Lines specifically focusing on Neutral Carbon Districts, aiming for transformative changes that extend beyond energy and greenhouse gas emissions, impacting all sectors and facets of city life [76].

**Table 2**  
List of experts.

| Id.  | Expertise      | Position      |
|------|----------------|---------------|
| En-1 | Energy         | Civil service |
| En-2 | Energy         | Academia      |
| En-3 | Energy         | Academia      |
| En-4 | Energy         | Academia      |
| PP-1 | Public policy  | Civil service |
| PP-2 | Public policy  | Civil service |
| PP-3 | Public policy  | Civil service |
| PP-4 | Public policy  | Academia      |
| U-1  | Urban planning | Civil service |
| U-2  | Urban planning | Academia      |
| U-3  | Urban planning | Academia      |

#### 4.2. Experts selected

A group of experts is consulted in the validation stages of the model, weighting criteria and evaluation of districts. Eleven practitioners form this group of experts from different fields working for the City Hall or involved in the Missions Valencia 2030 initiative. The areas of expertise were selected after the literature review and considering clusters associated with the criteria and according to the needs of the case study. For example, in terms of ICT, all districts have smart meters and any refurbishment, urban planning change or new energy system can be monitored without relevantly depending on the characteristics of the different neighbourhoods of a city. However, some cities in countries such as Germany have yet to complete the introduction of smart metering and would require decision-makers with ICT expertise to analyse the differences. Thus, the three fields of expertise selected for Valencia are: Energy [77,78], Urban planning [72,73] and Public policy, thus covering the diversity of approaches to promote PEDs [28,71]. Table 2 classifies the experts by expertise field and professional position.

#### 4.3. Alternatives analysed

València has 87 neighbourhoods, 19 administrative districts and 23 functional areas. Given the high number of neighbourhoods and the range of criteria, the evaluation of influences is unapproachable with the MCDM methodology proposed. Furthermore, the neighbourhoods are often too small for the definitions of PED found in the literature and promoted in the EU. Functional areas and administrative districts comprise different zones with broad similarities (more significant and sufficiently populated areas overlap each other in many cases). Fig. 2 shows the map of València divided into the 19 administrative districts.

Ultimately, the decision to focus on administrative districts is grounded in practicality. Administrative districts provide a more accessible source of statistical data, streamlining the research process. This choice is further reinforced by the understanding that smaller divisions hinder the different use types (residential, commercial, industrial), contributing to the PEDs' achievability and familiarity of the experts, whose judgements are pivotal in the methodology used, with this division of the city. Collecting data at these smaller divisions would also present significant challenges. Therefore, considering the overarching goal of conducting a comprehensive pre-evaluation of the entire city, administrative districts emerge as the most suitable spatial scale for analysis. This choice aims to balance meaningful evaluation criteria and the practicality of data collection, facilitating the assessment of PED achievability.

## 5. Results and discussion

This section presents the results and discussion of the prioritisation of PED for the case study of València. First, in Section 5.1, criteria are validated, and a final list of criteria is provided to prioritise between the 19 districts of the city of València. The final list of criteria is the

result of phase 2 — Validation of the model (3.3). The initial list of 36 criteria is reduced to 19, allowing for a more concise and agile list to continue with the following phases of weighting criteria and evaluation of districts. Then, Sections 5.2 to 5.4 present the results of the prioritisation of the districts and the criteria. The study analyses the overall results of the prioritisation, the partial results, and the results by each expert type. This analysis allows us to observe the different importance levels of the criteria depending on the district under consideration. But also under the different experts' perspectives according to their field of expertise.

#### 5.1. Selection of the criteria based on a Delphi strategy

Starting with the initial list of criteria (Table 1), a Delphi procedure was employed to validate the main criteria pertinent to the València case study. Validation of the criteria through a Delphi procedure occurred in two rounds. First, experts answered about the criteria's influence on achieving feasible PEDs. The questionnaire also provided their reasons for their judgements (importance scores). The CDI index for the first round was 0.3. Then, a second round was conducted, including anonymous information from the first questionnaire. The second questionnaire was personalised for each expert. It included graphs with the frequency of responses (from 0 to 4), the mean value, the comments of the other experts, and the expert's value in the previous round. Then, experts were asked to review their judgement based on the others' judgements and reasoning or to maintain their earlier assessments. After various rectifications, the CDI index for the second round was under 0.2, within the preset threshold.

After the Delphi, the values of all the experts are aggregated, with the arithmetic mean, and then the criteria are arranged from highest value to lowest value. The selected criteria (marked in purple in Fig. 3) are the ones that account for 60% of the accumulated value. Using the defined scale from 0–4, the values represent the importance of each criterion for the objective of the feasibility of the PED; see Fig. 3. The criteria were reduced to 19, allowing a more agile process of consultations and a more precise interpretation of the results.

The 19 criteria include at least two criteria from each cluster. There are at least two criteria from each cluster in the list of 19 criteria (see Table 3), confirming the importance of the feasibility of the PED for the criteria in each of the five clusters. Thus representing the importance of a multi-criteria analysis due to the criteria diversity.

#### 5.2. Overall DEMATEL results

In the particular case of this study, based on the available quantitative information, differentiated by districts, collected by the different services of the Valencia City Council, the districts' evaluation for each criterion was as shown in Table 4. The qualitative criteria are evaluated by direct assessment based on the 0–4 scale (Section 3.3.2). The quantitative criteria are evaluated by a transfer function that transforms actual data into a value in the 0–4 scale (Section 3.3.3). As can be seen, most of the criteria lacked quantitative information or were not district-specific. On the other hand, and as discussed below, the criteria classified as most influential agree that they should be evaluated qualitatively. This finding has made it possible to identify what information is missing in the city's tracking and monitoring systems for its plans to become carbon neutral by 2030.

For the criteria with quantitative information, the information was compiled, and ad-hoc transfer functions were proposed to the experts. Once agreement was reached, all evaluated the criteria in the same way, unlike the evaluations of the qualitative criteria, which showed differences among the experts for each district. Fig. 4 shows the seven transfer functions for each criterion.

After applying the DANP method, the prioritisation of districts depends on their potential to become PEDs. The method prioritises criteria from the most to the least important for a feasible PED to

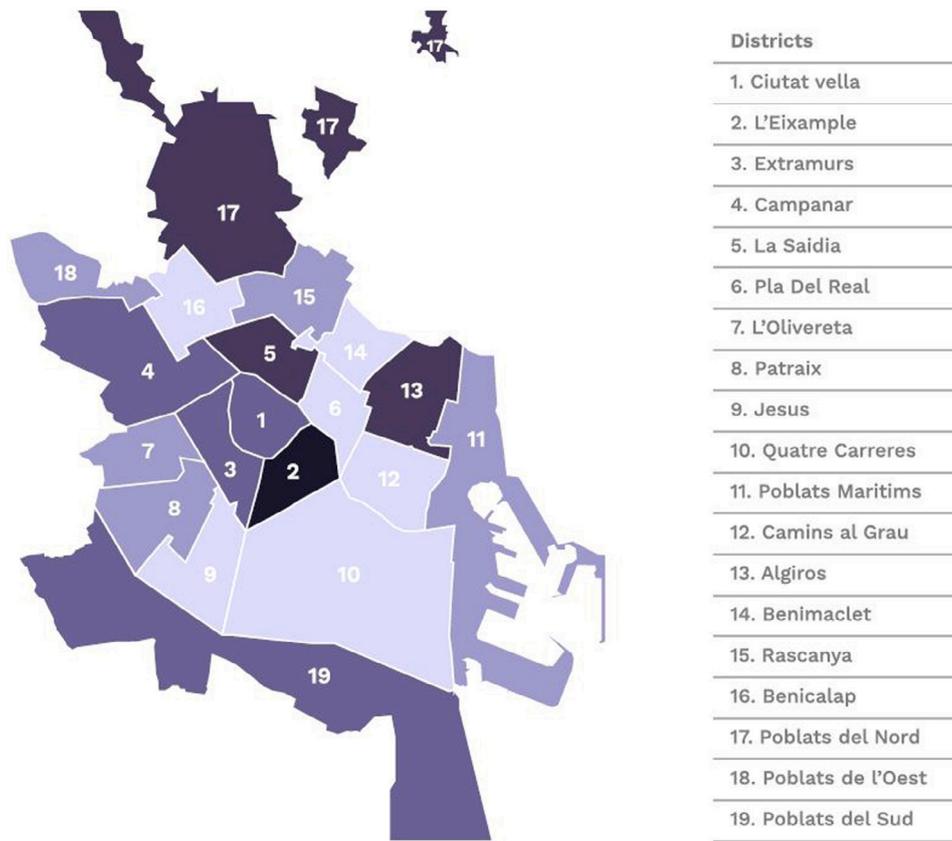


Fig. 2. Administrative districts of Valencia.

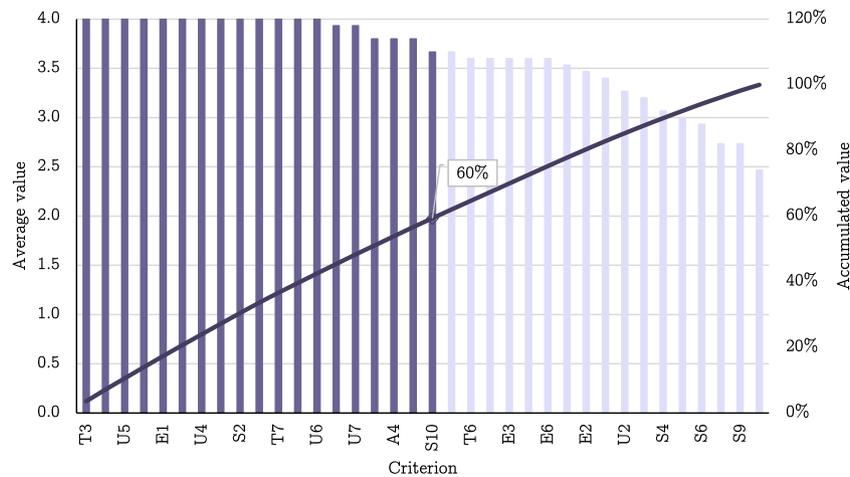


Fig. 3. Weight of criteria in Delphi round 2.

be obtained. The prioritisation of districts for the group of experts is shown in Fig. 5. Three groups of districts are observed from the most to the least outstanding in the ranking. The best districts for the location of feasible PEDs are Poblots Marítims, Benimaclet, Benicalap, Pobles Oest and Campanar. The following group comprises Pobles Sud, Rascanya, Algirós, Pobles Nord, Quatre Carreres, Jesús, Patraix and Saldia. Finally, the districts with the least potential are Ciutat Vella, Eixample and Extramurs.

The districts belonging to each of these groups have similar characteristics. The best-ranked districts are located in the outskirts, with more available space and modern constructions, among other features. The least suitable districts are located in the city centre. The historic districts, among other characteristics, have less space and older

constructions, many protected by heritage status, and more complex rooftops. The intermediate districts in the prioritisation are also the middle case between the characteristics described. From a technical point of view, those differences condition the energy demand, renewable energy production capacity and energy efficiency, which will be more challenging in the historic districts.

The final average weight of each criterion for the group of experts is shown in Fig. 6. The four criteria with the highest weighting are two economic criteria, one technical and one social, in the following order: investment (E1) and the potential for improving the energy efficiency of buildings and activities (T7), interest or acceptance (S1) and subsidies or projects (E5). Following these four criteria come current developments in mobility (U7), community organisation (S3),

**Table 3**  
Final list of criteria by cluster.

| Technical cluster  | Social cluster                                | Urban cluster                             | Environmental cluster                          | Economic cluster       |
|--|---|---|--|------------------------|
| T1. Renewable energy resources   | S1. Interest or acceptance                    | U4. Area per capita                       | A1. GHG emissions                              | E1. Investment         |
| T3. Renewable energy resource potential  | S2. Cooperative projects                      | U5. Surface of public buildings and plots | A4. Average air pollution in the neighbourhood | E5. Grants or projects |
| T4. Annual electricity consumption per capita in the neighbourhood                                 | S3. Community organisation                    | U6. Total area of green areas             |  |                        |
| T5. Annual thermal consumption of the neighbourhood per capita                                     | S5. Urban ecology and sustainable initiatives | U7. Current developments in mobility      |  |                        |
| T7. Potential for improving the energy efficiency of buildings and activities in the neighbourhood | S7. Fuel poverty                              |   |  |                        |
|  | S10. Population                               |   |  |                        |

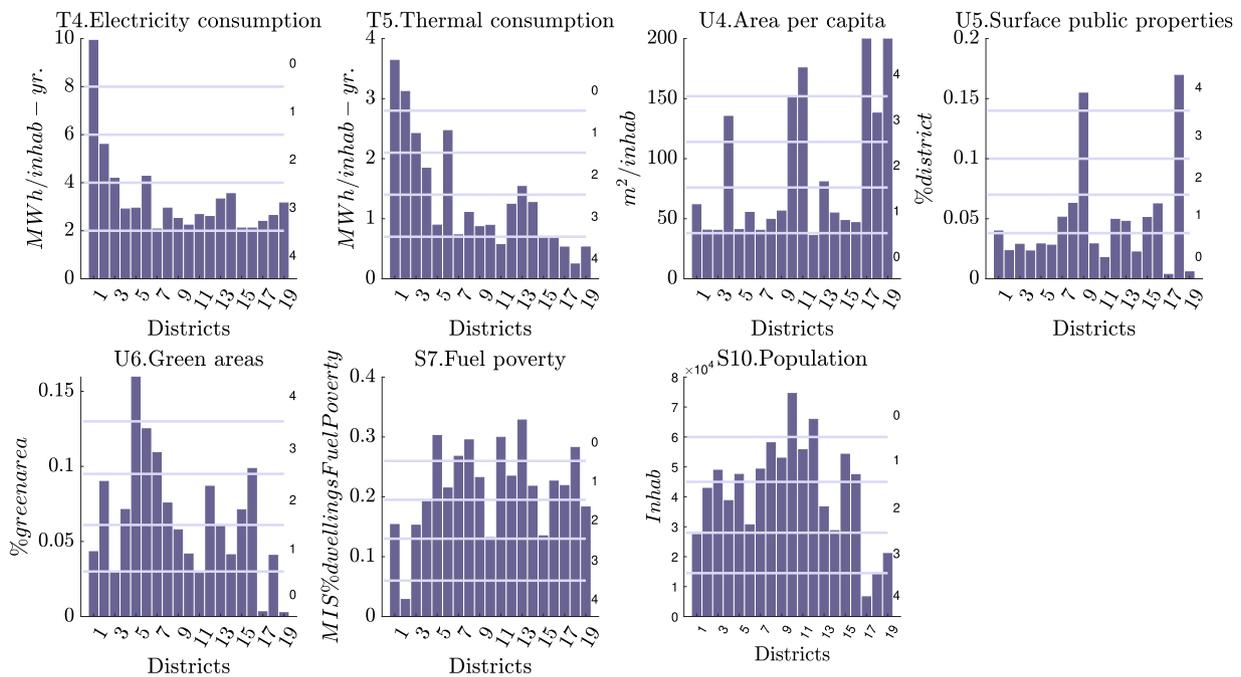


Fig. 4. Transfer functions.

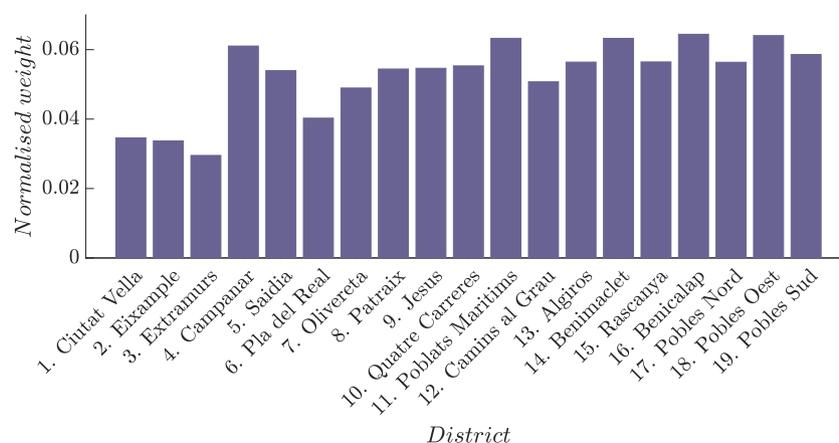


Fig. 5. Aggregated value of districts.

thermal consumption per capita (T5), cooperative projects (S2), renewable energy resources (T1), electricity consumption per capita (T4), and population (S10). Next up are the two environmental criteria, the district’s average air pollution (A4) and GHG emissions (A1), followed by the area per capita (U4) and the total area of green spaces (U6),

the potential for utilisation of renewable energy resources (T3), fuel poverty (S7) and finally the total size of public buildings and plots (U5).

The results of the prioritisation of criteria highlight the importance of economic criteria, although social, technical, and urban criteria are also among the most relevant. The least relevant is the environmental

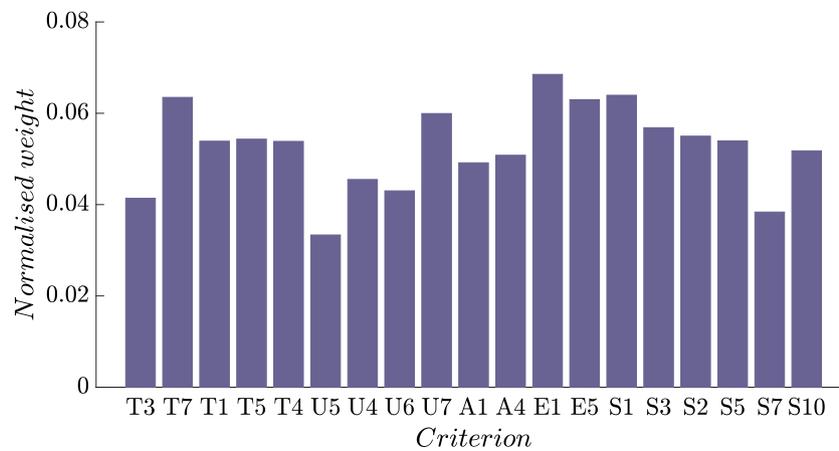


Fig. 6. Aggregated weight of criteria.

Table 4

Classification of qualitative and quantitative criteria.

| Qualitative  | Quantitative   |
|--|--|
| T1. Renewable energy resources   | T4. Annual electricity consumption per capita in the neighbourhood |
| T3. Renewable energy resource potential  | T5. Annual thermal consumption of the neighbourhood per capita     |
| T7. Potential for improving the energy efficiency of buildings and activities in the neighbourhood | S7. Fuel poverty   |
| S1. Interest or acceptance   | S10. Population  |
| S2. Cooperative projects   | U4. Area per capita  |
| S3. Community organisation   | U5. Surface of public buildings and plots                          |
| S5. Urban ecology and sustainable initiatives  | U6. Total area of green areas                                      |
| U7. Current developments in mobility   |  |
| A1. GHG emissions  |  |
| A4. Average air pollution in the neighbourhood   |  |
| E1. Investment   |  |
| E5. Grant or projects  |  |

cluster, which is also the cluster whose criteria are more affected by the criteria from other clusters, the technical and urban clusters. Therefore, it is partially reflected in other criteria. Although the five clusters were found relevant for the objective of a feasible PED, the dependence of the environmental cluster on others ranks its criteria lower in the prioritisation.

### 5.3. Partial analysis of the results

Logically, each criterion has a different influence in each district. For each of the 19 districts, Fig. 7 represents the influence of the five criteria having the highest aggregated weight. For example, the Extramurs district has a high level of interest or acceptability (S1), while others, such as Pobles de l'Oest, have a lower level. The same applies to grants or projects (E5), with a higher incidence in districts such as Poblat Maritims, Extramurs or Benicalap than in others like Jesús or Rascanya. The potential for improving the energy efficiency of buildings and activities (T7) is unexpectedly lower in districts where the average building age is high (Ciutat Vella and l'Eixample).

Nevertheless, this is due to the greater protection of the constructions by heritage status, which means insulation and retrofitting will be more challenging. In terms of investment (E1), there are no significant changes. However, districts such as Pobles de l'Oest, Jesús, and Benimaclet score lower, probably due to their lower average per capita income, which means higher public support will be needed.

The current developments in mobility (U7) are the criterion shown in Fig. 7 that reveals the most significant variation among districts, and the comparison in Fig. 8 is interesting in this regard.

Fig. 8 illustrates the scores for each district on the map for the criteria Renewable energy resources (T1) and Current developments in mobility (U7). Given the increased need for public transport connections and quality improvements in bike mobility, the districts that have made the most progress in mobility are the most central ones, as shown on the map. While the results indicate that a plan is needed to increase this criterion's score in the outlying districts, their distance from other parts of the city makes this a more complicated problem. In the case of the Renewable Energy Resources (T1) score, however, districts on the city's outskirts have more resources available than those in the city centre. Districts on the city's outskirts have more area for installing renewable energy production systems, and some even border the sea, increasing the resources available (e.g. marine energy and better wind power). In contrast, the more central districts have a higher urban density and more heritage buildings.

### 5.4. Analysis by expert bias

Expert groups disaggregate the scores for each criterion, and Fig. 9 represents the results. As can be seen, there are no very relevant differences among the average profiles of the groups. The potential for improving the energy efficiency of buildings and activities (T7), investment (E1), and fuel poverty (S7) are examples of criteria that have high agreement among different expert groups. There are, however, criteria that show distinct values for each expert profile. These disparities arise from the different perceptions of the interactions between criteria or between criteria and alternatives. The population (S10) is one of those cases. The energy expert group considered the population more important than the public policy expert group. However, the public policy expert group thought GHG emissions were more important than they were for the energy expert group. The energy expert group perceives that GHG emissions have little influence over other criteria but are heavily influenced by them. In contrast, they believed that the population density strongly influences other criteria but is not significantly affected by them.

Grants and projects (E5) are more relevant for energy and urban planning experts than public policy experts. The surface of public buildings and plots is more relevant for energy and urban planning experts than public policy experts. In these cases, for which the assessment of criteria versus alternatives depended on the experts' perception and not on quantifiable data, the differences are due not only to different perceptions of criteria influences on criteria but also to different perceptions between criteria and alternatives.

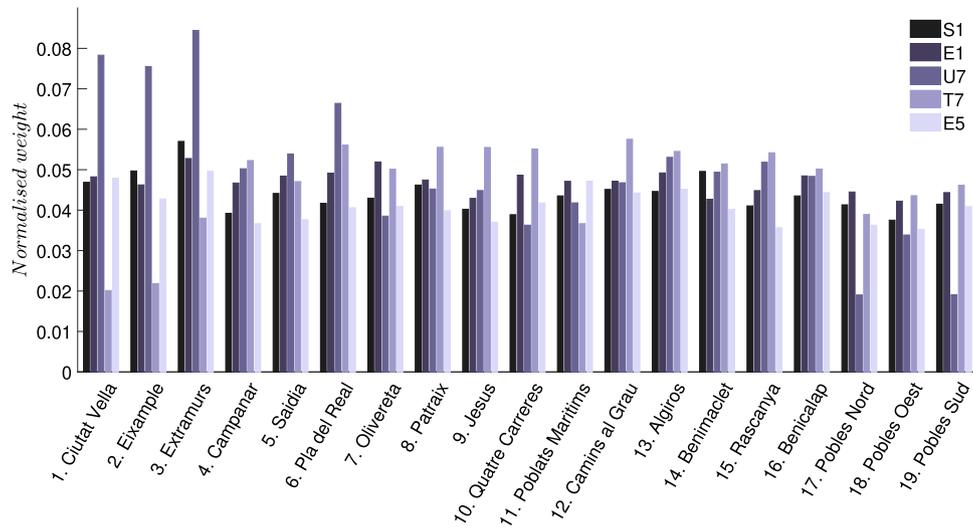


Fig. 7. Weight of the five main criteria in each district.

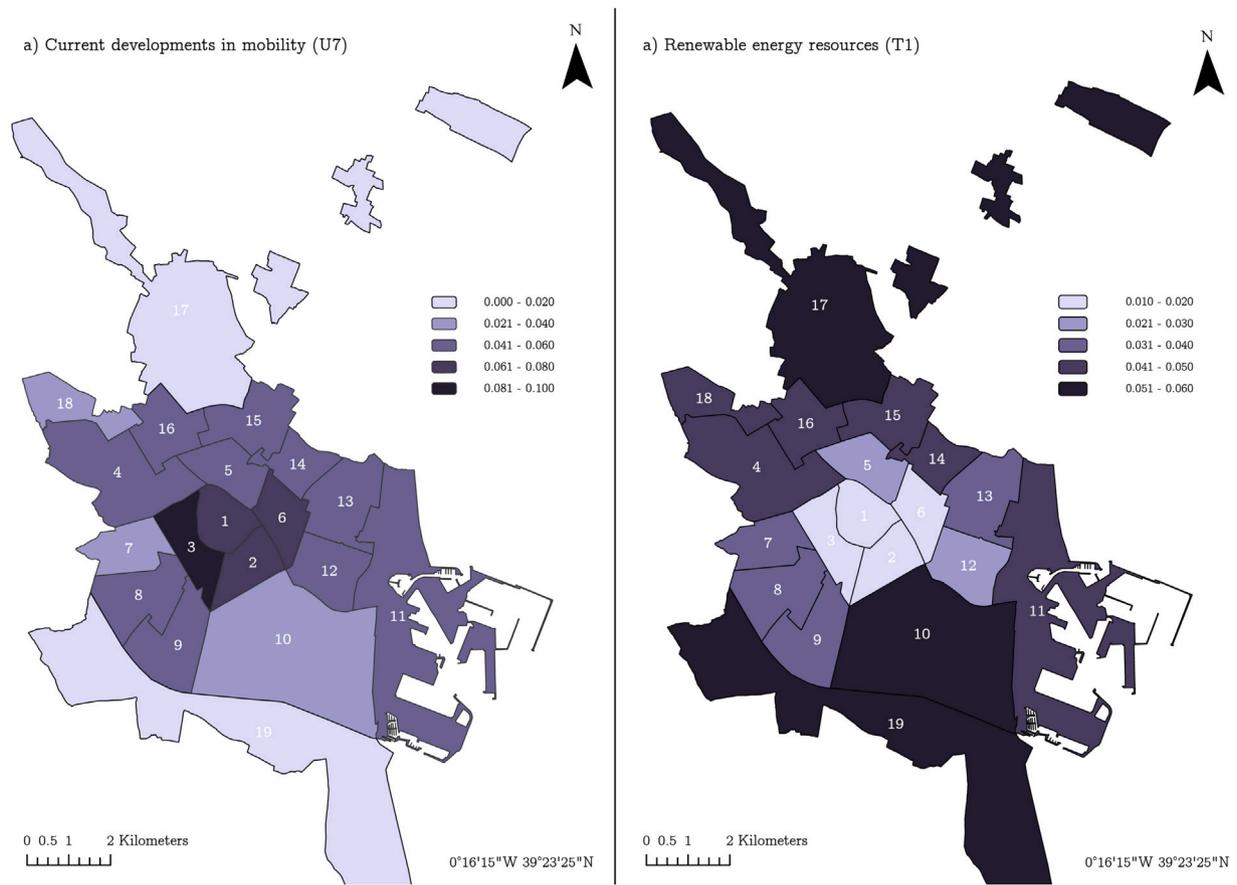


Fig. 8. Maps of the criteria weights for each district for U7 and T1.

The scores for each criterion disaggregated by experts' affiliation are represented in Fig. 10. For some criteria, there are relevant differences whether the experts are from academia or civil service. The most considerable discrepancies are in the importance of the social cluster criteria, grants and projects (E5) and (T3) renewable energy resource potential. Grants and projects and renewable energy resource potential serve as the main criteria for civil service experts, although their significance is not as pronounced within academia. The population (S10)

and the interest or acceptance (S1) are considered more important for academia than the civil service. While civil service gives more importance to Urban ecology and sustainable initiatives(S5).

These results highlight the bias that exists depending on the type of expert. The importance of certain criteria is perceived differently depending on both the expert's field and their professional affiliation. The inclusion of multidisciplinary teams in decision-making processes has the potential to mitigate the impact of such biases.

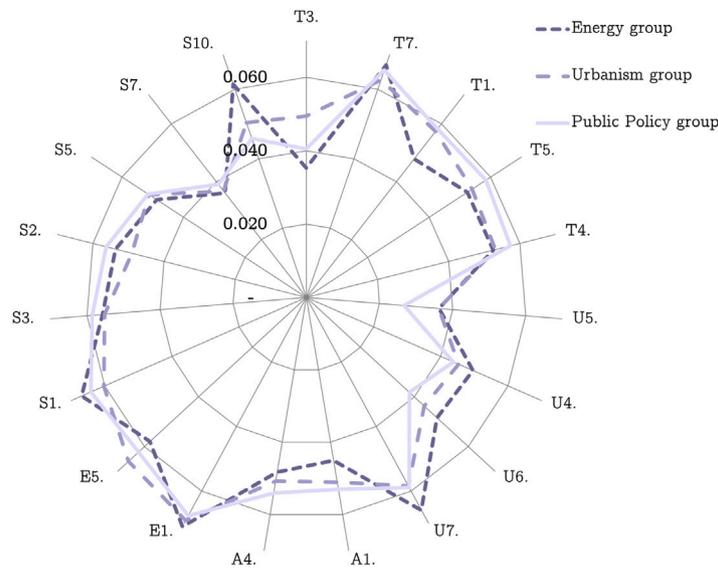


Fig. 9. Aggregated weight of criteria by expert group.

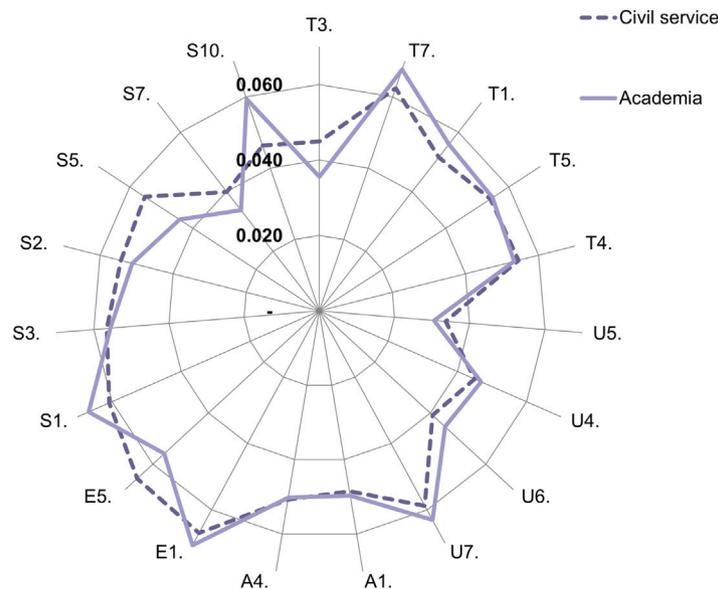


Fig. 10. Aggregated weight of criteria by expert affiliation.

5.5. Policy implications and further work

PED initiatives are crucial in shaping the two primary urban policies under development in Europe. Firstly, the Urban Agenda for the EU aims to instigate a structural shift in energy systems, acknowledging the indispensable role of the local level. It particularly underscores the district level as a practical and manageable scale for citizen engagement in energy transition processes [79]. On the other hand, the Cities Mission seeks to deliver one hundred climate-neutral and smart cities in Europe by 2030, showcasing how to expedite urban climate transitions. It recognises the value of experimenting at the district level and subsequently scaling up at the city level [80]. Considering these initiatives, the methodology presented in this study holds several key policy implications for urban policies.

Firstly, it enables local authorities to incorporate a holistic approach to assessing different city districts, facilitating better-informed decisions on PED policy deployment. This inclusive approach considers all relevant dimensions of PED development, encompassing not only technological and economic aspects but also vital urban considerations

such as social equity, democratic participation, engagement, cultural identity, and acceptance of initiatives.

Secondly, clustering different districts based on diverse, relevant criteria, as illustrated in Fig. 5, is a valuable tool for defining the deployment locations of key demonstrative projects and determining the scaling-up process. According to the Climate Mission, achieving climate neutrality is an iterative learning process. This clustering could pinpoint districts that offer valuable insights for replication in similar areas.

Thirdly, the methodology is place-based, involving the selection of specific experts for a participatory analysis of districts in each city. This approach presents a crucial opportunity for the City Council to consult various stakeholders, opening up the decision-making process to diverse perspectives. While this study has focused on public administration and academia, stakeholders may span different innovation helixes, including public institutions, private companies, local workers, civil society representatives, academia, and media. Analysing and clustering stakeholders can provide the City Council with a richer understanding of diverse interpretations for deploying PED policies in the city.

Finally, further research work on the methodology may open policy implications on how to focus specific technological, economic, social or governance innovations in each specific PED project. By pondering the criteria, the methodology allows policymakers to identify the most suitable districts to deploy specific innovations in PEDs policy deployment. Assessing social issues or participatory engagement in different districts enables City Councils to determine which areas are most suitable for governance innovations in PED initiatives, with a focus on social concerns or participatory processes. These experimental initiatives may nurture the replication and scaling up processes, considering the similarities or differences with other districts. Additionally, assessing the different districts may be useful for defining the local technological roadmap to deploy in each district and identifying which would be the most appropriate district where technological solutions could be profitably tested to replicate them in other districts.

Consequently, the methodology presented in this study is valuable for implementing a city-level policy on deploying PED district policies within an overarching city strategy that emphasises the sustainable, social, and democratic components of urban energy transition processes.

## 6. Conclusions

This study introduces a comprehensive methodology for prioritising and understanding the potential for various urban districts within a city to transition into Positive Energy Districts (PEDs), guided by previously selected criteria. The initial phase involves selecting criteria following a literature review. These criteria are then categorised into five clusters aligned with the PED definition, encompassing technical, urban, environmental, economic, and social considerations. A panel of experts well-versed in carbon-neutral districts across European cities is assembled. Subsequently, a Delphi procedure, employing questionnaires, is employed to validate key criteria pertinent to the case study, allowing for a more agile process and a more precise interpretation of the results. The DANP is utilised to apply the selected criteria to different districts as alternatives, providing a comprehensive analysis of critical elements in assessing a district's suitability for becoming a PED. This analytical framework aids in designing strategies to foster the transformation and the differences that arise from one district to another.

The methodology is applied to a specific case study: Valencia, Spain, recognised as one of the initial ten European cities honoured with the European Union's Mission Label for its decarbonisation commitment. The Action Plan of Valencia features a specific Action Line dedicated to Neutral Carbon Districts, envisioning transformations that span all sectors and aspects of city life. The findings from the case study reveal that the best-ranked districts, situated on the outskirts with more available space and modern constructions, contrast with the less suitable historic districts in the city centre. Outskirts districts offer ample space for renewable energy production systems and, in some instances, are adjacent to the sea, augmenting available resources.

In contrast, the more central districts have a higher urban density and more heritage buildings. In the overall ranking of criteria, the highest-scoring criteria are two economic criteria, one technical and one social, in the following order: investment and the potential for improving building energy efficiency, interest or acceptance, and subsidies or projects. The importance of various criteria for achieving PED varies depending on the area's characteristics. Therefore, different measures should be implemented in different kinds of districts.

Moreover, a study of these characteristics establishes the basis of complementary strategies between districts. For example, high-income Ciutat Vella can benefit from the likely surplus of energy generation in the Campanar district while financially supporting the retrofit of Campanar homes to save energy. It is noteworthy that practitioners from different expertise fields yield distinct results for the prioritisation

of criteria, underscoring the importance of multidisciplinary teams in decision-making processes.

This proposed methodology serves as a valuable tool for decision-making in a city's urban energy planning. Identifying the most relevant criteria for PED status in each city district enables decision-makers to strategically promote measures aligned with these criteria, consolidating the city's decarbonisation on a district-by-district basis. The holistic approach encourages better-informed decisions on where to deploy PED policies, including not only technological and economic issues but also crucial urban questions such as social equity, democratic participation and engagement or cultural identity and acceptance of initiatives. Further research work on the methodology may open policy implications on how to focus specific technological, economic, social or governance innovations in each specific PED project.

## CRediT authorship contribution statement

**I. Aparisi-Cerdá:** Writing – original draft, Methodology, Visualisation, Data curation. **D. Ribó-Pérez:** Conceptualization, Methodology, Software, Data curation, Visualisation, Writing – original draft, Writing – review & editing. **T. Gómez-Navarro:** Conceptualization, Writing – review & editing, Supervision. **M. García-Melón:** Methodology, Writing – original draft. **J. Peris-Blanes:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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