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Development of methodologies for energy planning of urban districts with just energy transition perspective

by

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Abstract

Climate change has emerged as a globally acknowledged challenge, necessitating coordinated and decisive action through robust policies, investments in clean technologies, and shifts in consumption and production patterns. Within this context, the energy transition stands out as a key strategy to mitigate the effects of climate change, with cities playing a fundamental role. However, cities' diverse socio-economic and spatial characteristics present significant challenges to achieving an equitable energy transition.

Given the complexity of urban landscapes and the decentralised nature of renewable energy production, there has been a growing need to reevaluate urban energy planning strategies, focusing on urban districts as the primary unit of analysis. This approach enables collective systems to optimise the available space more effectively.

This doctoral thesis proposes methodologies for energy planning in cities and at the district scale that support actions targeting not only decarbonisation objectives but also social inclusion goals, to ensure an inclusive energy transition, focusing on Valencia as a case study. The research begins a multi-criteria decision-making methodology to prioritise districts for transformation into (Positive energy districts) PEDs. Subsequently, a PED planning methodology is formulated and applied to Urban Waterfronts (UWF), considering their potential and the results of the previous prioritisation.

The methodology for PED planning in UWF suggests that the proposed actions be based on established objectives and a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. Social inclusion must be made explicit for a residential district; otherwise, it will not occur based solely on decarbonisation objectives. By proposing a multi-criteria selection methodology similar to the first one, we aim to analyse changes in the selection of actions for decarbonisation when considering only decarbonisation criteria or gender criteria, along with the diversity of expertise among decision-makers. Finally, to illustrate how to implement specific strategies for inclusive decarbonisation, a proposal to contribute to fostering urban shared self-consumption of photovoltaic electricity while mitigating energy poverty is outlined.

The findings of this thesis highlight the need to continue advancing in the development of methodologies that not only address the technical and environmental

challenges of urban energy transitions but also ensure that these transitions are socially inclusive. Through close collaboration with local stakeholders and policymakers, it is possible to develop and apply methodologies that support a city's broader urban planning goals. This thesis underscores the value of integrating academic research with real-world urban challenges to help guide the city's transition toward a more sustainable and equitable future.

Resumen

El cambio climático se ha convertido en un desafío globalmente reconocido, que requiere una acción coordinada y decisiva a través de políticas robustas, inversiones en tecnologías limpias y cambios en los patrones de consumo y producción. En este contexto, la transición energética se destaca como una estrategia clave para mitigar los efectos del cambio climático, con las ciudades desempeñando un papel fundamental. Sin embargo, las diversas características socioeconómicas y espaciales de las ciudades presentan desafíos significativos para lograr una transición energética equitativa.

Dada la complejidad de los paisajes urbanos y la naturaleza descentralizada de la producción de energía renovable, ha surgido la necesidad de reevaluar las estrategias de planificación energética urbana, centrándose en los distritos urbanos como la unidad principal de análisis. Este enfoque permite que los sistemas colectivos optimicen el espacio disponible de manera más efectiva.

Esta tesis doctoral propone metodologías para la planificación energética en ciudades y a escala distrital que apoyen acciones dirigidas no solo a objetivos de descarbonización, sino también a metas de inclusión social, para asegurar una transición energética inclusiva, centrándose en Valencia como caso de estudio. La investigación comienza con una metodología de toma de decisiones multicriterio para priorizar distritos para su transformación en Distritos de Energía Positiva (PEDs). Posteriormente, se formula una metodología de planificación para PEDs y se aplica a los Frentes Marítimos Urbanos (UWF), considerando su potencial y los resultados de la priorización previa.

La metodología para la planificación de PEDs en UWF sugiere que las acciones propuestas se basen en objetivos establecidos y un análisis DAFO. La inclusión social debe hacerse explícita para un distrito residencial; de lo contrario, no se logrará solo con los objetivos de descarbonización. Al proponer una metodología de selección multicriterio similar a la primera, se pretende analizar los cambios en la selección de acciones para la descarbonización cuando se consideran solo los criterios de descarbonización o los criterios de género, junto con la diversidad de experiencia entre los tomadores de decisiones. Finalmente, para ilustrar cómo implementar estrategias específicas para una descarbonización inclusiva, se esboza una propuesta para contribuir a fomentar el autoconsumo compartido de electricidad fotovoltaica en entornos urbanos mientras se mitiga la pobreza energética.

Los resultados de esta tesis destacan la necesidad de seguir avanzando en el desarrollo de metodologías que aborden no solo los desafíos técnicos y ambientales de las transiciones energéticas urbanas, sino que también aseguren que estas transiciones sean socialmente inclusivas. A través de una estrecha colaboración con actores locales y responsables políticos, es posible desarrollar y aplicar metodologías que apoyen los objetivos más amplios de planificación urbana de una ciudad. Esta tesis subraya el valor de integrar la investigación académica con los desafíos urbanos del mundo real para ayudar a guiar la transición de la ciudad hacia un futuro más sostenible y equitativo.

Resum

El canvi climàtic s'ha convertit en un desafiament globalment reconegut, que requereix una acció coordinada i decisiva a través de polítiques robustes, inversions en tecnologies netes i canvis en els patrons de consum i producció. En aquest context, la transició energètica es destaca com una estratègia clau per mitigar els efectes del canvi climàtic, amb les ciutats jugant un paper fonamental. No obstant això, les diverses característiques socioeconòmiques i espacials de les ciutats presenten desafiaments significatius per aconseguir una transició energètica equitativa.

Donada la complexitat dels paisatges urbans i la naturalesa descentralitzada de la producció d'energia renovable, ha sorgit la necessitat de reavaluar les estratègies de planificació energètica urbana, centrant-se en els districtes urbans com a unitat principal d'anàlisi. Aquest enfocament permet que els sistemes col·lectius optimitzen l'espai disponible de manera més efectiva.

Aquesta tesi doctoral proposa metodologies per a la planificació energètica en ciutats i a escala distrital que recolzen accions dirigides no només a objectius de descarbonització, sinó també a fites d'inclusió social, per assegurar una transició energètica inclusiva, centrant-se en València com a cas d'estudi. La investigació comença amb una metodologia de presa de decisions multicriteri per prioritzar districtes per a la seua transformació en Districtes d'Energia Positiva (PEDs). Posteriorment, es formula una metodologia de planificació per a PEDs i s'aplica als Fronts Marítims Urbans (UWF), considerant el seu potencial i els resultats de la priorització prèvia.

La metodologia per a la planificació de PEDs en UWF suggereix que les accions proposades es basen en objectius establerts i una anàlisi DAFO. La inclusió social s'ha de fer explícita per a un districte residencial; en cas contrari, no s'aconseguirà només amb els objectius de descarbonització. En proposar una metodologia de selecció multicriteri similar a la primera, es pretén analitzar els canvis en la selecció d'accions per a la descarbonització quan es consideren només els criteris de descarbonització o els criteris de gènere, juntament amb la diversitat d'experiència entre els prenedors de decisions. Finalment, per a il·lustrar com implementar estratègies específiques per a una descarbonització inclusiva, s'esbossa una proposta per a contribuir a fomentar l'autoconsum compartit d'electricitat fotovoltaica en entorns urbans mentre es mitiga la pobresa energètica.

Els resultats d'aquesta tesi destaquen la necessitat de continuar avançant en el desenvolupament de metodologies que aborden no només els desafiaments tècnics i ambientals de les transicions energètiques urbanes, sinó que també asseguren que aquestes transicions siguen socialment inclusives. A través d'una estreta col·laboració amb actors locals i responsables polítics, és possible desenvolupar i aplicar metodologies que recolzen els objectius més amplis de planificació urbana d'una ciutat. Aquesta tesi subratlla el valor d'integrar la investigació acadèmica amb els desafiaments urbans del món real per ajudar a guiar la transició de la ciutat cap a un futur més sostenible i equitatiu.

Contents

Chapter 1

Introduction

This thesis adopts the journal compilation format, consisting of four papers published in JCR journals. It is organized into seven chapters, beginning with an introduction that outlines the background, objectives, methodology, and structure. The core of the thesis is represented by the next four chapters, which include the journal articles. The sixth chapter provides the discussion, while the seventh presents the main conclusions and future research directions. The final chapter summarizes the publications and research project participation that occurred during the development of this thesis.

1.1 General context

Climate change is of paramount concern due to its widespread and devastating effects on ecosystems, the economy and society [1]. Scientific evidence, supported by leading institutions such as the World Meteorological Organisation (WMO) and the Intergovernmental Panel on Climate Change (IPCC), shows a significant increase in global temperatures, melting of the poles, rising sea levels, increased frequency and intensity of extreme weather events and ocean acidification, among other phenomena [2]. These changes directly affect food security, public health, freshwater availability, biodiversity and geopolitical stability [3]. In addition, climate change exacerbates social and economic inequalities, disproportionately affecting the world's most vulnerable and marginalised communities [3].

In response, the international community recognises the urgent need for action to reduce greenhouse gas emissions, adapt to the unavoidable impacts of climate change and enhance societal resilience [4]. The scale and severity of these challenges require coordinated and decisive action on a global scale, supported by robust policies, investments in clean technologies and changes in consumption and generation patterns.

At the 2023 United Nations Climate Change Conference (COP28), commitments towards decarbonisation have been strengthened, with more precise plans outlined to limit the global temperature rise to 1.5°C. COP 28 marked the first 'global stocktake' of the world's efforts to address climate change under the Paris Agreement. The global greenhouse gas emissions need to be cut 43% by 2030, compared to 2019 levels, to limit global warming to 1.5°C [4]. The stocktake urges countries to make significant efforts to achieve ambitious targets on a global scale. This includes tripling renewable energy capacity, doubling energy efficiency improvements by 2030, and accelerating efforts to progressively eliminate coal power and phasing out fossil fuels in a fair, orderly and equitable manner.

The international community has recognised the importance of aligning climate actions with social goals, particularly by the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015. The Sustainable Development Goals (SDG) recognise that ending poverty and other deprivations must go together with strategies that improve health and education, reduce inequalities and stimulate economic growth while tackling climate change.

At the European level, the European Commission (EC) has laid out ambitious targets concerning greenhouse gas (GHG) emission reductions, energy efficiency, and the penetration of renewable energy sources (RES). The ultimate aim for 2050 is to achieve zero net emissions. To reach this goal, the Commission has set interim targets for 2030, including reducing at least 55% in GHG emissions, attaining 32% of primary energy consumption from RES, and achieving a 32.5% improvement in energy efficiency [5]. Energy transition has emerged as a critical element in both national and local strategies to achieve the objectives set by international agreements and mitigate climate change by reducing GHG emissions [6].

1.2 Background

1.2.1 Local approach to the energy transition

While energy transition at the national level is central to global policy frameworks and large-scale infrastructure development, transition at the local level plays a critical role in implementing and scaling up these efforts [7]. National policies outline the direction of the energy transition, set renewable energy targets, incentivise adoption and facilitate inter-regional grid connections. Conversely, local initiatives are indispensable to tailor solutions to communities' specific needs and circumstances. These initiatives can focus on community-driven projects such as rooftop solar installations, building retrofits to improve energy efficiency, and decentralised energy systems. These local efforts often yield immediate benefits, driving community engagement and supporting broader national energy objectives.

At the local scale, cities are seen as critical to advancing the sustainable development agenda. Globally, urban populations comprise more than half of the world's 8 billion people, and projections indicate an increase in the proportion of urban population from 56% today to approximately 70% between 2024 and 2050. Projections also suggest expanding urban areas by approximately 1 million km^2 by 2050. Cities currently account for more than 75% of global energy consumption and around 70% of energy-related CO_2 emissions. In particular, almost 10% of the increase in global emissions since 2015 can be attributed to urbanisation [8]. Nevertheless, cities also emerge as epicentres of knowledge, technology and innovation, given their significant impact on the environment and society beyond their borders [9]. Driven by their population density, economic importance and resource demand, cities emerge as key drivers of sustainability transitions.

In Europe, cities cover 4% of land area and 75% of the population [10], underlining their key role in achieving the 2050 climate neutrality target set out in the European Green Deal. European cities have the potential to contribute significantly to emission reduction targets and, at the same time, to offer their inhabitants cleaner air, safer transport and reduced congestion and noise. Hence, one of the European Union's (EU) five missions, the Climate-Neutral and Smart Cities mission, focuses on decarbonising cities [11]. The mission aims to achieve 112 climate-neutral smart cities by 2030 and ensure that these cities serve as centres of experimentation and innovation, leading all European cities to follow suit by 2050.

Seven Spanish cities, including Valencia, have been selected by the European Commission for the Climate-Neutral and Smart Cities mission, demonstrating Spain's commitment to sustainable urban development. Valencia, in particular, has been recognised as a European Green Capital and Innovation Capital in 2024. Spain's commitment to energy transition is further evidenced by initiatives such as the draft Climate Change and Energy Transition Law (LCCTE) [12], the National Integrated Energy and Climate Plan (PNIEC) [13], and the Just Transition Strategy (ETJ) [14]. These frameworks aim to achieve 100% renewable electricity and greenhouse gas neutrality by 2050, reduce emissions by 23% by 2030, and ensure social equity in the transition process.

Despite these efforts, achieving an equitable energy transition in cities poses challenges due to their diverse socio-economic and spatial characteristics. While inclusiveness is emphasised in initiatives like the Climate-Neutral and Smart Cities mission, specific guidelines targeting vulnerable groups are lacking. Overcoming these challenges is essential for realising the full potential of sustainable energy transitions in cities. Thus, this thesis will explore urban energy planning methodologies from a just transition perspective.

1.2.2 Just transition of cities

The transition to a low-emission energy model is an opportunity for a more socially inclusive system, but it does not inherently lead to it; it can, in fact, perpetuate existing inequalities, such as social and gender disparities, energy vulnerability, and passive citizen participation without specific attention to these issues [15]. The challenge extends beyond those displaced by the decline of the fossil fuel industry to include others on the frontline of the clean energy transition [16].

Energy justice emphasises that everyone should have access to energy that is affordable, safe, sustainable, and capable of supporting a decent lifestyle, along with the opportunity to participate in and lead energy decision-making processes with the authority to enact change [17]. Without an energy justice framework, the transition can adversely affect individuals, households, and communities globally.

Achieving a just energy transition requires international, national, regional, and local agreements, actions, and policies. Each level presents unique challenges and opportunities. Internationally, it is crucial to address material extraction, ensuring fair conditions for the land and affected populations [18]. Nationally, employment policies, retraining programs, regulations, and subsidies can support communities most affected by the transition [19]. Regionally, efforts can promote the acceptance of renewable energy projects by involving local communities in planning and ensuring their benefit through job creation and community investments [20]. Locally, the focus should be on including the most vulnerable citizens in decentralised energy production systems, improving transportation and urban planning for all, and increasing the energy efficiency of buildings, particularly for low-income households [21].

To ensure a just transition in cities, it is crucial to implement inclusive and participatory governance strategies that address urban inequality. Community-centred approaches are increasingly being developed to accelerate the transition to clean and efficient energy systems. These initiatives enable individuals and communities to actively participate in clean energy transitions, building trust, enhancing public acceptance, and supporting affordability, equity, and fairness [8]. Digital technologies, such as smart meters and management systems, create new opportunities for setting up cooperatives, engaging stakeholders, making investments, and exchanging electricity [8]. However, studies show that without inclusive approaches, the benefits of the energy transition are likely to be unevenly distributed, exacerbating existing social inequalities and energy injustices [22].

Cities can promote a socially inclusive transition that reduces emissions and enhances social equity by addressing the needs of their most vulnerable populations [21]. Achieving this requires implementing specific actions and approaches tailored to these communities [15]. Therefore, this thesis proposes a dual approach for a just energy transition: first, considering both climate and social justice criteria in the selection stages of actions or measures to be implemented, specifically focusing on the gender perspective; and second, proposing specific actions aimed at leveraging the transformative potential of the energy transition, such as collective self-consumption systems to mitigate the consequences of energy poverty.

The emphasis on these two areas is primarily due to the significant magnitude of gender disparity in urban settings and, secondly, to the direct relationship between energy poverty and the energy transition. Both issues represent major challenges in the context of urban injustices. Gender disparity affects the fair distribution of resources and opportunities, while energy poverty directly impacts the ability of disadvantaged groups to participate in and benefit from the energy transition.

Gender disparity is identified as a major challenge in addressing urban injustices [23]. The intersectionality of gender compounds this issue with other forms of inequality, such as class, race, and access to resources, which further marginalises women, especially those from poorer backgrounds [24, 25]. Women from low-income households and marginalised ethnic groups face multiple layers of discrimination that intersect and amplify their overall marginalisation. Cultural and societal norms often dictate traditional gender roles that limit women's access to education and formal employment opportunities, confining them to undervalued and unpaid domestic work. Furthermore, health disparities disproportionately affect women, particularly in low-income and rural areas, limiting their capacity to engage fully in economic and social activities.

Research in gender studies demonstrates how policies and actions lacking a gender perspective often result in gender biases [26]. Policies and actions that do not incorporate a gender perspective tend to reinforce existing inequalities and fail to meet the specific needs of women. For instance, economic policies without a gender lens might overlook barriers to women's employment and fail to address wage gaps, thus perpetuating economic inequalities [27]. Similarly, healthcare policies that do not consider gender-specific health issues can lead to inadequate healthcare services for women, particularly in reproductive health [28]. Additionally, social policies that ignore gender dynamics often fail to address the disproportionate burden of unpaid domestic work that falls on women, thereby limiting their economic opportunities and reinforcing traditional gender roles [29]. These biases not only perpetuate existing gender inequalities but also undermine the overall effectiveness of policies by neglecting the unique challenges faced by women [28].

Addressing these gender disparities is crucial for equitable urban development. Although climate change and its related policies are likely to have profound consequences for gender relations [30], policies focus on the economic and technical aspects, with justice issues, such as gender inequalities, playing a marginal role [31]. Studies focus on gender inequalities in relation to the energy transition in countries of the global south [23] or in relation to energy poverty [32], another key challenge of a just energy transition. In the urban context of the global north, there are also other challenges related to gender and mobility [33], the energy sector [34], climate policies [35], or decision-making and participation [36] among others related to class, income [25] or race [24]. However, previous studies do not quantify the effects of urban policies simultaneously in gender and climate spheres or assess the bias produced due to the expertise field of the decision-makers. A just transition is not limited to outlining a specific set of policies and processes; instead, it promotes a shared vision and inclusive planning and decision-making that engages all affected stakeholders in a way tailored to local circumstances [37]. Therefore, this thesis will analyse the implications of considering gender as well as climate criteria in the decision-making processes for selecting decarbonisation actions.

Regarding energy poverty, it represents both significant challenges and opportunities for the energy transition at a local level [38]. Energy poverty is a challenge for the energy transition because, without an adequate plan for the inclusion of this vulnerable group, their situation can worsen, as the measures associated with the energy transition involve initial investments that are not accessible to everyone. Moreover, subsidies for residential energy technologies often benefit wealthier groups disproportionately because they can afford the remaining investment costs. In contrast, lower-income households cannot do so, leading to increased inequality [39]. However, this transition also holds the potential for mitigating energy poverty through innovative solutions and targeted public policies. These efforts can enable vulnerable groups to benefit from collective self-consumption systems [40], simultaneously advancing the energy transition and reducing poverty.

1.2.3 The district scale

The complexity of urban landscapes, coupled with the decentralised nature of renewable energy production, has prompted a revaluation of urban energy planning strategies, focusing on urban districts as the primary unit of analysis. This decentralisation represents an opportunity for energy democratisation if considered from the beginning [41]. Furthermore, the neighbourhood-focused approaches can balance the economies of scale and specific tailored measures, enabling more systematic methods for achieving efficient and flexible electricity demand [8]. The goal is to establish Net Zero Energy Districts (NZEDs) or Positive Energy Districts (PEDs), fostering a balance between assessing the energy performance of buildings and their characteristics, considering urban planning and mobility in the area, and better integrating renewable energy generation and distribution systems, enabling collective systems to optimise available space [42]. Targeted initiatives and influential stakeholders have predominantly driven the advancement towards establishing PEDs. The Strategic Energy Technology Plan, launched by JPI Urban Europe, aims to develop 100 PEDs by 2025 [43]. This plan seeks to engage a wide range of stakeholders, including municipal authorities, research institutions, industrial partners, energy providers, and civic organisations. It underscores that

PEDs not only make significant contributions toward achieving the goals set by COP28 but also enhance the quality of urban life in European cities.

Moreover, the European Energy Research Alliance Joint Programme on Smart Cities has led the European Cooperation in Science and Technology action titled "PED-EU-NET Positive Energy Districts European Network." This initiative promotes open collaboration among stakeholders from diverse sectors [44]. On a global scale, the International Energy Agency has developed the Energy in Buildings and Communities Programme Annex 83, recognised as a leading platform for international scientific discourse and research on PEDs [45]. Annex 83 aims to establish a comprehensive framework for PEDs by analysing relevant technologies, planning tools, and decision-making processes. Collectively, these initiatives at both European and international levels have attracted increased interest and research in PEDs, encompassing both theoretical exploration and practical case studies.

While these initiatives highlight the technological advancements and collaborative efforts essential for PEDs, they also highlight that the broader challenge encompasses more than just technology [46]. Despite the importance of technological innovation, the challenge is not primarily technological but rather one of transforming services, management and policies [47]. Although it is known that different areas are involved (technical-energy, urban, economic, social), the interrelationships between these areas and how they may vary according to the initial characteristics of each district have not been studied in depth. Knowing these interrelationships would make it possible to identify the relevant criteria within these areas and to understand, characterise and make decisions when acting in one district or another. It will make it possible to take advantage of this intermediate scale and adapt energy and urban planning to the needs and characteristics of each district.

Therefore, holistic methodologies represent a promising approach for aiding decision-makers in prioritising and planning effective energy transition strategies within urban areas. This enables a comprehensive evaluation of diverse criteria, including technical, social, urban, environmental, and economic factors, to ensure well-informed and balanced decisions. Additionally, including the visions of different stakeholders captures diverse urban perspectives, allowing the engagement of various expert profiles, each contributing complementary perspectives, supporting the development of inclusive and comprehensive strategies.

Furthermore, structured local planning from a holistic perspective also fosters social innovation in energy, which involves a large variety of actors, actor networks, and institutional frameworks [48]. It is not at odds with participatory processes involving citizens [21], which have also been considered part of a just transition but can instead provide a framework for them.

Therefore, this thesis advocates for methodologies that empower decision-makers to handle intricate decision-making processes, even when confronted with uncertain and qualitative data [49], as is the case with energy transitions in urban environments [50, 51]. Additionally, it emphasises the importance of strategic planning for urban districts. These approaches facilitate a more comprehensive and balanced evaluation, integrating diverse technical, social, urban, environmental, and economic criteria. Consequently, they support the development of well-informed and effective energy transition strategies within urban areas.

1.3 Objectives

The main objective of this PhD is to generate comprehensive knowledge and develop practical methodologies and strategies that support the planning and implementation of a just energy transition in urban areas, aligning with the broader ambition of fostering sustainable, inclusive, and decarbonised cities. This goal is based on the necessity to understand the complexities and challenges of urban energy transitions, addressing the interrelations between technical, social, environmental, and economic factors.

To fulfil this main aim, the following specific objectives are proposed:

- **SO1. Establish a methodology for prioritising city areas to develop Positive Energy Districts:** This objective focuses on developing a robust methodology that integrates both quantitative and qualitative data, enabling local authorities to adopt a holistic approach in evaluating different city districts. It will provide a balanced and thorough assessment framework by considering comprehensive aspects related to the definition of PEDs—including technical, urban, environmental, economic, and social factors. This framework aims to assist local governments in making well-informed decisions about where to deploy PED policies, prioritising areas with the highest potential for positive impact.

- **SO2. Develop a planning methodology for Positive Energy Districts:** This specific objective aims to formulate an integrated planning methodology for PEDs that addresses various aspects of urban energy systems. This objective aims to formulate an integrated planning methodology for PEDs that addresses various aspects of urban energy systems. It aims to maximise renewable energy production and energy efficiency, ensuring these districts achieve a positive annual energy balance. It aims to provide a pathway for local authorities and stakeholders to plan and implement PEDs effectively.

- **SO3. Assess the impact of integrating gender equity in the energy transition:** The objective is to evaluate how the inclusion of gender criteria alongside climate goals influences the prioritisation of urban decarbonisation actions and supports a more equitable energy transition. It involves assessing urban policies through both climate and gender criteria and analysing how the prioritisation of decarbonisation actions varies when considering only climate criteria versus gender criteria and the effect of multidisciplinary decision-makers.

- **SO4. Address energy poverty within the energy transition:** This objective seeks to develop a specific proposal to mitigate energy poverty through the participation of vulnerable households in collective self-consumption systems. The research will compare the current solution of public subsidies with the integration of vulnerable households into shared photovoltaic systems to demonstrate the feasibility and benefits of the proposed approach. The proposal will contribute to both the energy transition and the mitigation of energy poverty.

1.4 Methodology

This thesis proposes methodologies for energy planning in cities and at the district scale that allow for the proposal of actions addressing not only decarbonisation objectives but also social inclusion goals, ensuring an inclusive energy transition. This thesis follows a transdisciplinary approach integrating different methods, which will be explained in detail in their respective chapters, to address the energy transition in cities in its techno-economic aspects, as well as to ensure a holistic vision of planning to guarantee a just transition.

Firstly, a multi-criteria decision methodology, based on Delphi and a combination of Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Analytic Network Process (ANP), is proposed for prioritising districts with the aim of transforming them into PEDs, with a case study in Valencia. Subsequently, a methodology for PED planning is developed and applied to the case study of Urban Waterfronts (UWF), given their potential in these environments and the results of the previous prioritisation. This methodology is based mainly on strategic planning for project management and the procedure for energy audits.

The methodology for PED planning in UWF suggests that the proposed actions be based on established objectives and a SWOT analysis. Social inclusion must be made explicit for a residential district, otherwise it will not occur based solely on decarbonisation objectives. By proposing a multi-criteria selection methodology similar to the first one, based on DEMATEL-ANP, the aim is to analyse changes in the selection of actions for decarbonisation when considering only decarbonisation criteria or gender criteria, along with the diversity of expertise among decision-makers. Finally, as an illustration of how to implement specific strategies for inclusive decarbonisation, a proposal aimed at contributing to fostering urban shared self-consumption of photovoltaic electricity while mitigating energy poverty is outlined. A techno-economic analysis is conducted to compare the proposal with the actual subsidies.

This research will focus on Valencia as a primary case study. Valencia serves as a common case study for this research due to its proactive stance and comprehensive planning towards climate neutrality. The Valencia 2030 Urban Strategy [52] provides a detailed roadmap for developing a sustainable, inclusive, and innovative city. This strategy, which integrates Urban Agenda principles with mission-oriented innovation policies, led to Valencia being chosen by the European Commission as one of the first cities to receive an EU Mission Label. This recognition underscores Valencia's commitment to achieving climate neutrality through implementing the Climate City Contract [53], which emphasises a just transition and the inclusion of vulnerable communities. Collaborating closely with policymakers in Valencia ensures that the methodologies and strategies developed in this PhD are practically applicable and address the city's specific needs.

1.5 Structure

Presented as a thesis by publication, the collection in this document forms a comprehensive work on the planning of urban districts, focusing on achieving a just energy transition. The document is organised into eight chapters. The first chapter presents the general approach and background of the thesis together with the objectives, methodology and structure.

Chapters 2 to 5 present the core publications that constitute this thesis. Chapter 2 addresses SO1 and includes the publication titled *"Prioritising Positive Energy Districts to Achieve Carbon Neutral Cities: A Delphi-DANP Approach."* Chapter 3 is dedicated to SO2 and features the publication titled *"Planning Positive Energy Districts in Urban Waterfronts: Approach to La Marina de València, Spain."* Chapter 4, focusing on SO3, includes the publication titled *"Assessing Gender and Climate Objectives Interactions in Urban Decarbonisation Policies."* Chapter 5 covers SO4 with the publication titled *"Panel or Check? Assessing the Benefits of Integrating Households in Energy Poverty into Energy Communities."*

Chapter 6 presents the general discussion, and Chapter 7 presents the conclusions of the thesis regarding the planning of the district's energy transition with an inclusive approach and presents future work proposals.

Finally, Chapter 8 ends with the list of published works in Journals and Conferences and the participation in research projects during the development of this PhD.

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Chapter 2

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

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

Isabel Aparisi-Cerdá, David Ribó-Pérez, Tomás Gómez-Navarro, Mónica García-Melón, Jordi Peris-Blanes. "Prioritising Positive Energy Districts to achieve carbon neutral cities: Delphi-DANP approach," Renewable and Sustainable Energy Reviews, vol. 203, pp. 114764, 2024.

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 (Investement 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.

Keywords

Positive energy districts; Urban Energy Transition; Carbon Neutral Cities; Delphi; DANP

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

2.1 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 Net Zero 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, 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 organizations. 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 2.2 discusses the current literature around PED, especially the selection and criteria, and Section 2.3 presents the methodology to assess PED based on different criteria. Section 2.4 presents the case study of València. Here, the study applies the methodology to obtain results. Section 2.5 shows the results from the analysis and their implications. Finally, Section 2.6 concludes by summarising the main findings.

2.2 Positive Energy Districts and decision making methods

2.2.1 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 adaptative 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.

2.2.2 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 six 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.

2.2.3 Multi Criteria Decision Methods

As seen in sections 2.2.1 and 2.2.2, 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].

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.

2.3 Methodology

The methodology used to approach this research is organised in three stages, as presented in Figure 2.3.1. Each major step is described in detail in sections 2.3.1 to 2.3.3.

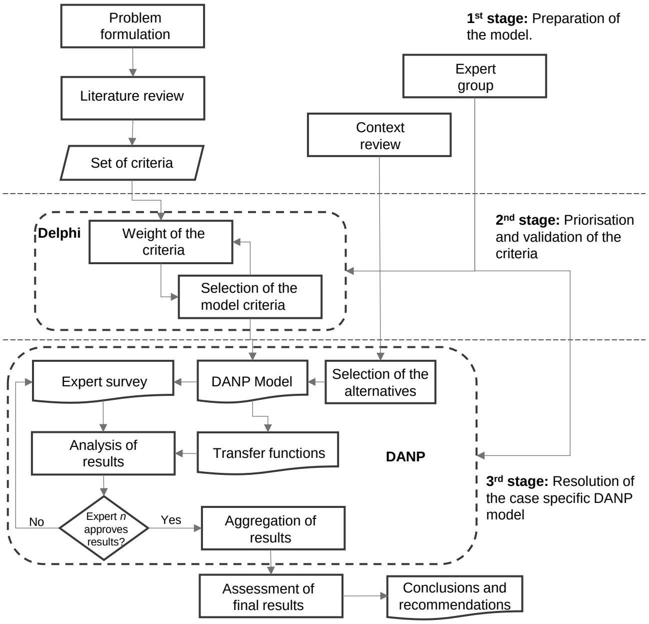

Figure 2.3.1: Summary of the followed methodology.

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 2.3.1).

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 [48], 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 2.3.3.3).

2.3.1 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 2.3.1) that could also be the starting list for any other European city.

2.3.1.1 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 2.3.1). The five clusters encompass the main aspects related to the definition of PED and are as follows. The 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 [49, 50]. The urban cluster groups together criteria related to the location, the typology of spaces in the neighbourhood, the built-up park, and mobility [51, 52]. The environmental cluster refers mainly to the visual impact on the landscape, air quality, noise pollution, and greenhouse gases [49, 51]. The economic cluster is focused on the investment capacity and costs of the necessary measures to achieve a PED [25, 49]. Finally, the social cluster is related to social aspects linked to the vulnerability of neighbours and their interest and involvement in a PED [28, 53].

Table 2.3.1: 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.	[54, 55]
T2	Current renewable generation	Total annual renewable generation of the district, prior to the PED project.	[32, 56]
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, 56]
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, 57]

	URBAN CLUSTER		
U1	District location	Location of the district in terms of climate vulnerabilities (higher temperatures, flood risk).	[58, 59]
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.	[60, 61]
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.	[62]
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, 63]
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.	[64]
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, 65]
E3	Investment capacity	District investment capacity for the project.	[32, 66]
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. In exchange, they concentrate actions in a single district.	[31, 66]
E6	Income	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, 66]
	SOCIAL CLUSTER		
S1	Interest or acceptance	From residents for the development of a PED project in their district and their participation in it.	[66, 67]
S2	Cooperative projects	Prior cooperative projects that have created a community in the neighbourhood.	[68]
S3	Community organisation	Residents' associations or other associations with active participation and involvement.	[69]
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: https://visor.gva.es/visor/)	[70]
S7	Fuel poverty	Complex concept mainly related to income, cost of energy and low energy efficiency of homes.	[71, 72]
S8	Affordable housing	Access to affordable housing and the availability of social housing.	[15, 73]
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.	[74]

2.3.1.2 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.

2.3.1.3 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.

2.3.2 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 minimizing 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:

$$CDI = \frac{S_{ij}}{\bar{X_{ij}}} \tag{2.3.1}$$

where, $\bar{X_{ij}}$ represents the average value of item ij 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.

2.3.3 Resolution of the DANP model

2.3.3.1 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 2.2.3:

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 nxn 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:

$$X = k \times A \tag{2.3.2}$$

$$k = \frac{1}{\max\limits_{1 \le i \le N} \sum_{j=1}^{n} a_{ij}} \tag{2.3.3}$$

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

Step 3: Attaining the total-relation matrix: T can be obtained by using (eq. 2.3.4), in which the I is denoted as the identity matrix.

$$T = X(I - X)^{-1} \tag{2.3.4}$$

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

$$w_{ij} = \frac{t_{ij}}{\sum_{i=1}^{n} t_{ij}} \tag{2.3.5}$$

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.

2.3.3.2 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.

2.3.3.3 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.

2.3.3.4 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.

2.4 Case study

2.4.1 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^2. The city's historic centre, spanning approximately 169 hectares, is one of Spain's largest.

Valencia experiences a hot-summer Mediterranean climate characterized 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 3,973 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.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].

2.4.2 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 [51, 52] and Public policy, thus covering the diversity of approaches to promote PEDs [28, 50]. Table 2.4.1 classifies the experts by expertise field and professional position.

Table 2.4.1: 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

2.4.3 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). Figure 2.4.1 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.

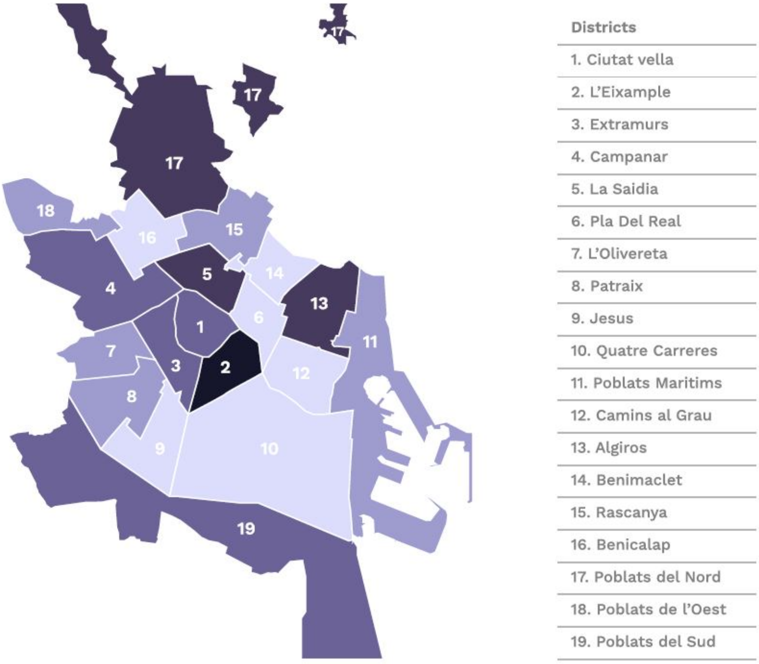

Figure 2.4.1: Administrative districts of Valencia.

2.5 Results and Discussion

This section presents the results and discussion of the prioritisation of PED for the case study of València. First, in section 2.5.1, 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 (2.3.3). 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 2.5.2 to 2.5.4 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.

2.5.1 Selection of the criteria based on a Delphi strategy

Starting with the initial list of criteria (Table 2.3.1), 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 Figure 2.5.1) 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 Figure 2.5.1. 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 2.5.1), 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.

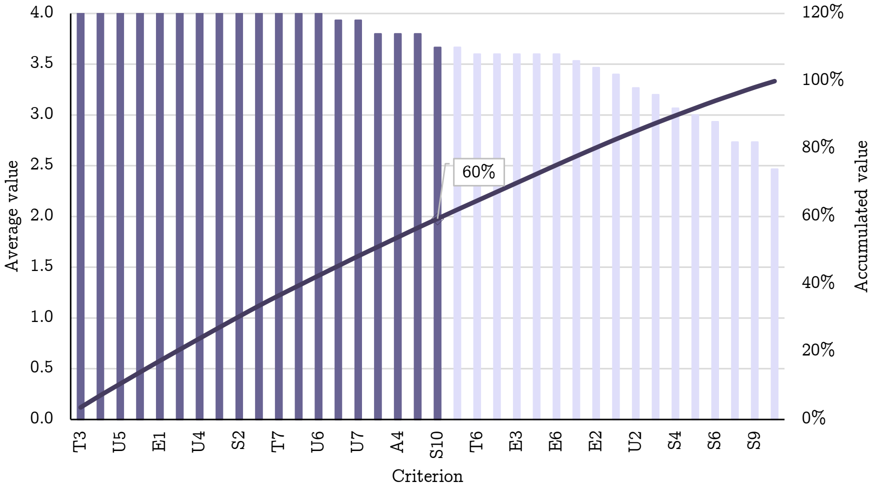

Figure 2.5.1: Weight of criteria in Delphi round 2.

Table 2.5.1: 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			

2.5.2 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 2.5.2. The qualitative criteria are evaluated by direct assessment based on the 0-4 scale (section 2.3.3.2). The quantitative criteria are evaluated by a transfer function that transforms actual data into a value in the 0-4 scale (section 2.3.3.3). 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.

Table 2.5.2: 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	

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. Figure 2.5.2 shows the seven transfer functions for each criterion.

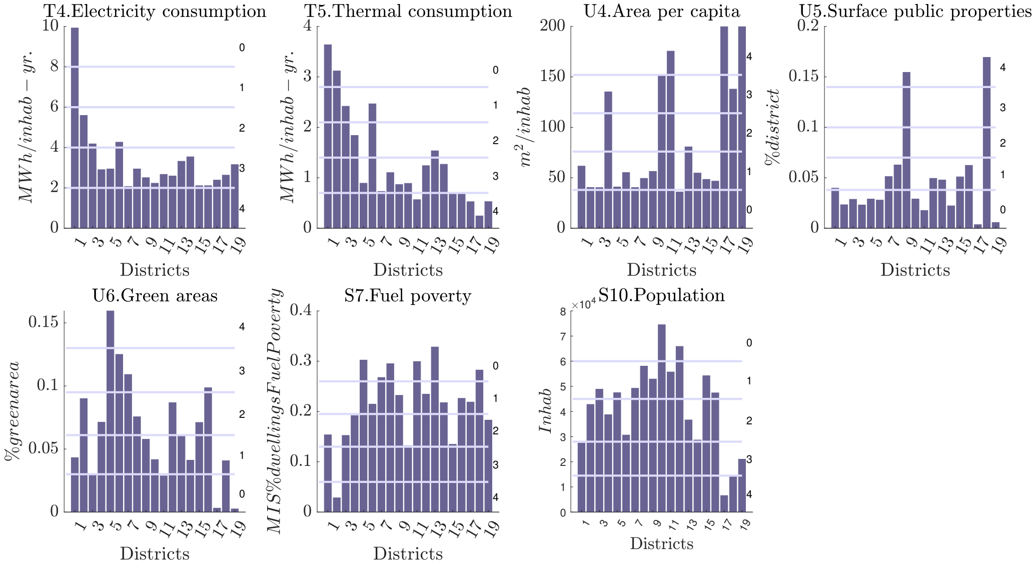

Figure 2.5.2: Transfer functions.

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 be obtained. The prioritisation of districts for the group of experts is shown in Figure 2.5.3. 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 Poblats Marítims, Benimaclet, Benicalap, Pobles Oest and Campanar. The following group comprises Pobles Sud, Rascanya, Algirós, Pobles Nord, Quatre Carreres, Jesús, Patraix and Saïdia. 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.

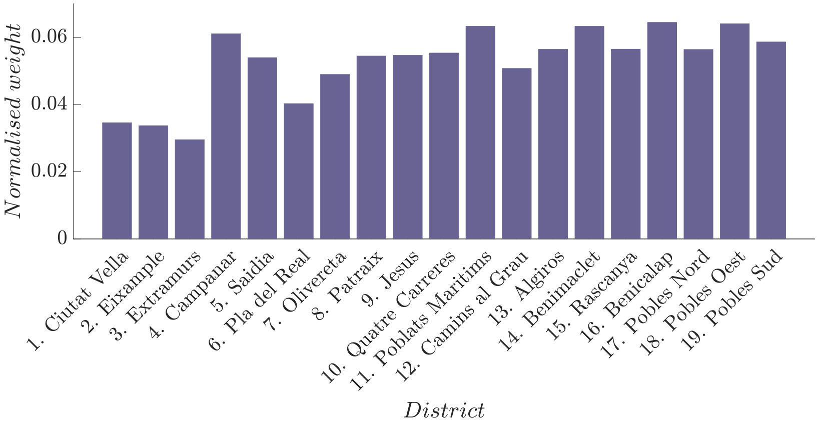

Figure 2.5.3: Aggregated value of districts.

The final average weight of each criterion for the group of experts is shown in Figure 2.5.4. 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), 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 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.

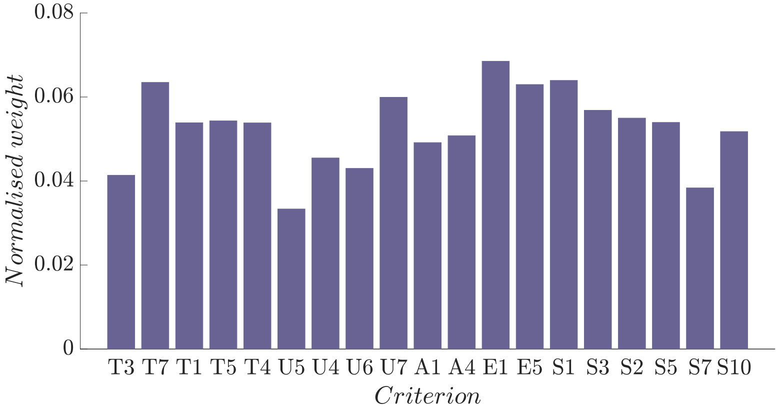

Figure 2.5.4: Aggregated weight of criteria.

2.5.3 Partial analysis of the results

Logically, each criterion has a different influence in each district. For each of the 19 districts, Figure 2.5.5 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 Poblats 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 Figure 2.5.5 that reveals the most significant variation among districts, and the comparison in Figure 2.5.6 is interesting in this regard.

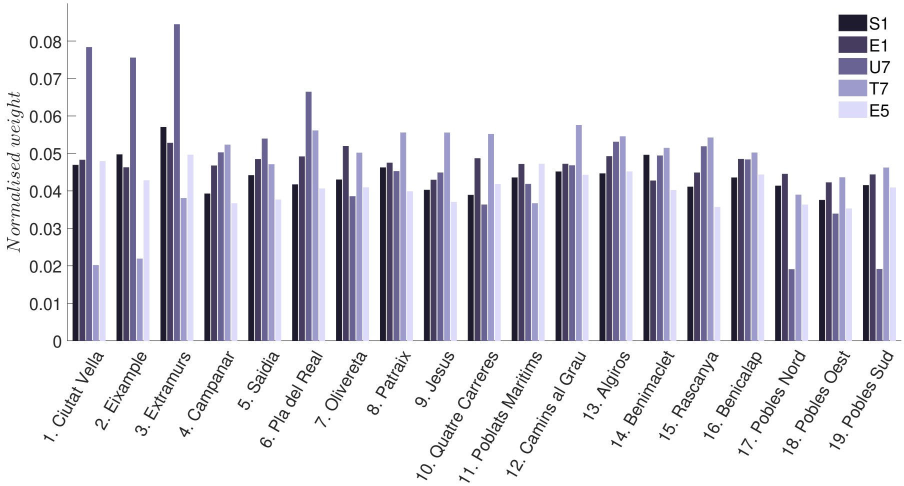

Figure 2.5.5: Weight of the five main criteria in each district.

Figure 2.5.6 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.

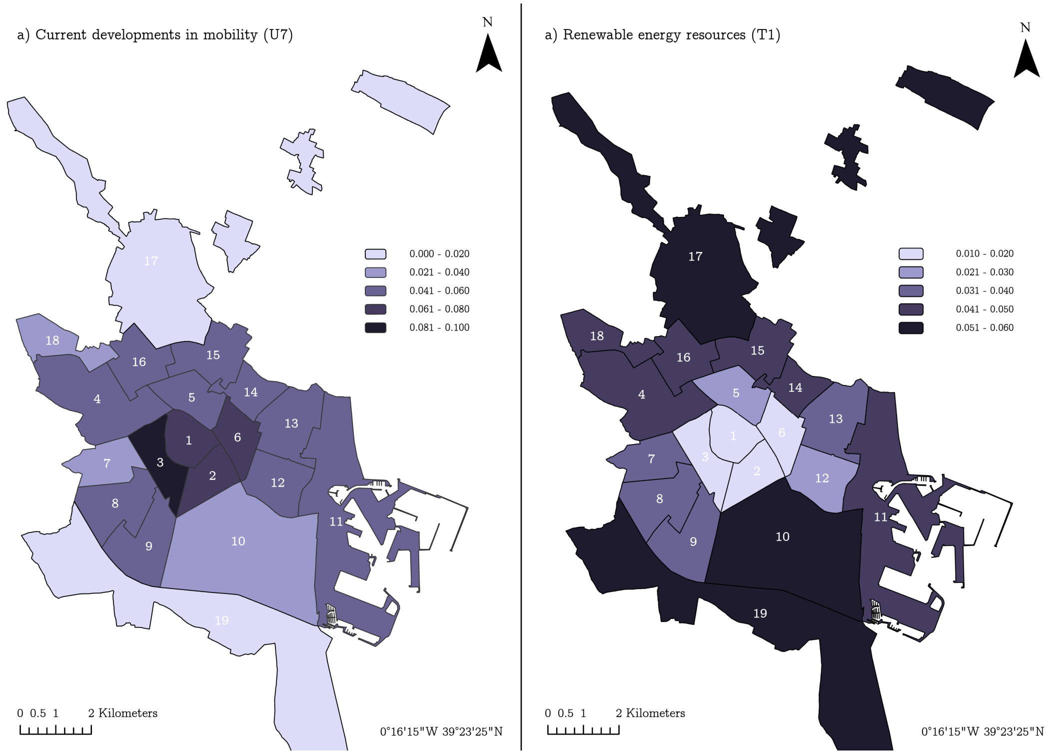

Figure 2.5.6: Maps of the criteria weights for each district for U7 and T1.

2.5.4 Analysis by expert bias

Expert groups disaggregate the scores for each criterion, and Figure 2.5.7 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.

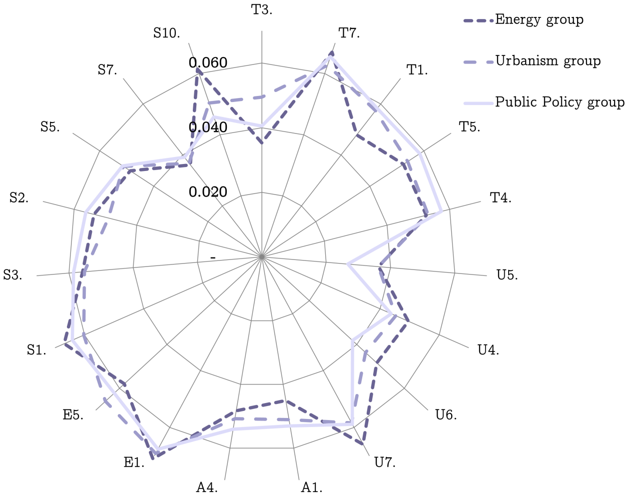

Figure 2.5.7: Aggregated weight of criteria by expert group.

The scores for each criterion disaggregated by experts' affiliation are represented in Figure 2.5.8. 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.

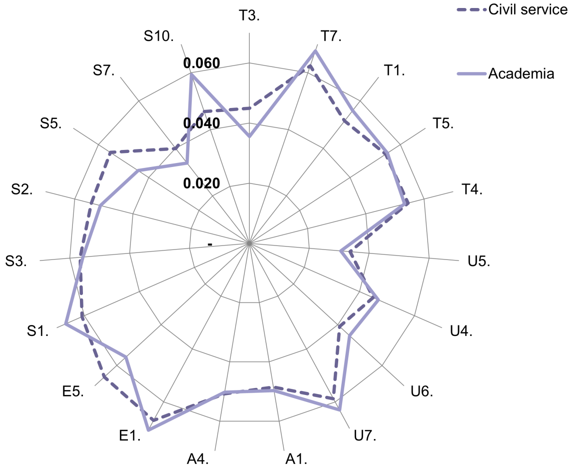

Figure 2.5.8: Aggregated weight of criteria by expert affiliation.

2.5.5 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 recognizes 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 Figure 2.5.3, 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. Analyzing 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 emphasizes the sustainable, social, and democratic components of urban energy transition processes.

2.6 Conclusions

This study introduces a comprehensive methodology for prioritizing 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 categorized 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 utilized 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, recognized as one of the initial ten European cities honoured with the European Union's Mission Label for its decarbonization 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 decarbonization 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

Isabel Aparisi-Cerdá: Writing - original draft, Methodology, Visualisation, Data Curation. David Ribó-Pérez: Conceptualization, Methodology, Software, Data Curation, Visualisation, Writing - original draft, Writing - review & editing. Tomás Gómez-Navarro: Conceptualization, Writing - review & editing, Supervision. Mónica García-Melón: Methodology, Writing - original draft. Jordi Peris-Blanes: Writing - review & editing.

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Chapter 3

Planning positive energy districts in urban waterfronts: Approach to La Marina de València, Spain

Planning positive energy districts in urban waterfronts: Approach to La Marina de València, Spain

Isabel Aparisi-Cerdá, David Ribó-Pérez, Iván Cuesta-Fernández, Tomás Gómez-Navarro. "Planning positive energy districts in urban waterfronts: Approach to La Marina de València, Spain," Energy Conversion and Management, vol. 265, pp. 115795-115809, 2022.

Abstract

Cities consume two-thirds of the energy supply, and 70% of carbon dioxide equivalent emissions come from urban environments. Positive Energy Districts are innovative tools to achieve energy and climate neutrality in cities. Positive Energy Districts are regions or neighbourhoods with a positive annual energy balance, obtained mainly through energy efficiency and energy generation from renewables. Urban Waterfronts are extended areas close to the sea, which makes them suitable for several types of production with renewables, therefore seeming to be a suitable location to develop Positive Energy Districts. This paper proposes a method that combines strategic planning for project management and the procedure for energy audits to design the optimal district configuration. The study presents and analyses the case of La Marina de València, a district in a Mediterranean city. Three strategic scenarios, both technically feasible and with a positive energy balance, are presented. All the alternatives include PV and switching to light-emitting diode in lighting. The different strategies presented together with a sensitivity analysis facilitate the decision-making process in energy planning and establish a common pathway to achieve Positive Energy Districts in Urban Water Fronts. The results suggest that urban waterfronts are uniquely suited to achieve a positive annual energy balance, thus emerging as a crucial springboard to provide traction to the positive energy districts policy agenda.

Keywords

Positive energy districts; Urban waterfronts; Renewable energy; Energy planning

3.1 Introduction

Interest in new energy models is growing, motivated by EU and international emission reduction targets [1]. Cities consume two-thirds of the energy supply, and 70% of carbon dioxide (CO_2) emissions come from urban environments, making cities a key agent in the ongoing energy transition [2]. Cities involve large concentrations of population and different activity types. They include residential, commercial, industrial areas and areas that combine these three types. Different uses and urban layouts affect energy consumption available resources and imply different energy planning strategies to make cities carbon neutral.

Cities can become a driving force to catalyse the energy transition. Urban planners are reconsidering how to approach energy planning and take urban districts as their unit of analysis to turn them into Net-Zero Energy Districts (NZED) or Positive Energy Districts (PED) whenever possible to deal with this complexity. The NZEDs are a step beyond the individual approach of Net-Zero Energy Buildings (NZEBs) [3]. They involve larger areas with different uses, spaces, and consumptions. This implies considering more variables and constraints to reduce consumption while increasing distributed renewable generation. The concept of NZED [4] refers to municipalities with objectives of reducing energy demand and including energy supply from renewable energy sources on a local and decentralised basis. These models combine energy objectives [5] with other sustainability criteria related, for example, to waste reduction and urban planning [6]. If NZED evolves from NZEB, the Positive Energy Districts (PED) concept is a step further from NZED. Unlike NZED, PED is not limited to a zero balance of imported energy and emissions. It aims to achieve a positive balance that allows sharing the energy surplus with nearby neighbourhoods or districts with fewer possibilities or resources. Nevertheless, PED has ambitious objectives that face difficulties in built-up districts.

Today PEDs are still an innovative concept under development. A programme from the JPI Urban Europe, the PED and Neighbourhoods for Sustainable Urban Development, aims to support the planning, deployment, and replication of 100 Positive Energy Neighbourhoods by 2025 [7]. The programme provides a multi-stakeholder platform to develop implementation pathways, exchange information, experiences, and visions with other European cities, forming a European Positive Energy Cities network and funding concrete initiation projects. For this purpose, they developed the Reference Framework for Positive Energy Districts and Neighbourhoods [8] and the Implementation Plan [9].

The measures to address PEDs are in three main energy efficiency areas: energy efficiency, renewable generation, and reliability. These aspects will be interdependent in some of the actions undertaken. Energy production in PEDs is based on maximising renewable energy supply based on a locally distributed Renewable Energy System (RES) within the district's geographical boundary and through local energy sources adjacent to the district. Energy efficiency measures will contribute to reducing energy consumption. These measures encompass balancing different sector needs, building insulation and orientation, energy, and transport and mobility. PED also involve flexibility for energy usage within the districts. Along these lines Kılkış et al. [10] went even further and proposed another concept Net-Zero Exergy Districts based upon the quality of energy. Furthermore, not only new urban development areas but also the existing building stock both need to be addressed [11].

Citizens' involvement strategies and political support are considered the main success factors for PED development [7]. Implication and collaboration with citizens and end-users from the beginning will avoid their reluctance to the change of paradigm that a PED implies in social, economic, and energy aspects. Political support is necessary to activate programmes and develop new funding opportunities since access to funding and business models has been shown to remain the main barrier. In Europe, the JPI programme is facilitating the evolution of methodologies for developing PEDs in cities, but this point is still under development given its novelty. Along these lines, but referring to an entire city, [12] presents a methodology for integrated city energy modelling and assessment, from characterising the city's current energy performance to developing and assessing future scenarios. Bottom-up approaches are combined with top-down data for the energy characterisation, and scenarios are developed through a multi-criteria impact assessment model. Most authors have studied PEDs with case studies, i.e., Calise et al. in Naples [13]. Brozovsky et al. [14] conducted a state of the art review and observed that more than half of the reviewed papers applied their research to case studies. Other authors have studied a methodology, its objectives and phases and its replication, i.e. Alpagut et al. [15]; some have conducted a techno-economic analysis for high-suffiency districts, to find cost-optimal solutions, i.e. Laitinen et al. [16].

PEDs are challenging but there has been meaningful progress in developing renewable energy technologies and methods that can contribute to the energy transition and Clime Target Plan [17]. The review on renewable energy technology status for sustainable development by Østergaard et al. [18] showed recent progress. Repowering wind farms with the latest technologies is profitable. Moreover, there are still unexploited wind, wave, and solar power resources, among others. Photovoltaic (PV) systems are improving their performance and feasibility. Furthermore, despite its lesser maturity, wave energy's suitability for sustainable energy supply has been proven. Integrated and hybrid energy systems have demonstrated their relevance because they can integrate fluctuating renewables and exploit synergies through sector integration [19]. Therefore, spaces that can combine several of these renewable energy production systems have a significant potential to contribute to the energy transition. Ports and Urban waterfronts meet these characteristics.

3.1.1 Ports

The initiatives in the energy transition in the European Union ports of Valencia [20] [21], Hamburg [22], Amsterdam [23], and Rotterdam [23, 24] are summarised in Table 3.1.1 as a representative sample of the main sustainability initiatives for ports. In all of them, the reduction of CO2 emissions is sought to be in line with the Climate Target Plan's European objectives. They all resort to energy production, as ports in terms of space and resources are often rich environments. The leading technologies are PV panels and wind turbines. Efficiency is also present but without the same importance in all cases; interest in electric mobility and alternative fuels seems more substantial.

Table 3.1.1: Ports measures.

	Renewable energy generation	**Efficiency measures**	**Emissions plan**	**Electric mobility**	**Alternative fuels**	**References**
Valencia Port	PV project	LED	Reduction	Progressive replacement	LNG, CNG	[20, 21]
Hamburg Port	Wind power, PV, Solar thermal	-	Reduction	AGVs	-	[22]
Amsterdam Port	Wind power, PV, biomass	Shared Energy Platform	Reduction	-	LNG, H2	[23]
Rotterdam Port	Wind power, PV, biomass	Residual heat recovery	Reduction and capture	E-trucks	LNG	[25] [24]

3.1.2 Urban Waterfronts

Urban waterfronts (UWF) are among the most favourable environments for PEDs in coastal cities since they usually present different space and resources options; however, their potential is still unstudied. A UWF is the port district or the coastal area of a town. They are usually defined as old ports reconverted into industrial, residential or commercial areas due to the growth of a larger commercial port. Redefining these spaces' use has a crucial role in cities, promoting one or another sort of development for the city. UWFs are particularly interesting in energy terms since they have great renewable generation possibilities near urban centres, allowing for an energy surplus that could be shared with nearby city areas.

The main actions taken in 5 waterfronts, Victoria and Alfred (V&A) Waterfront in Cape Town, Torre Annunziata in Naples, Schoonschip in Netherlands, Zero Village Bergen in Norway and Gruž in Dubrovnik, Croatia, are summarised in Table 3.1.2. Those waterfronts were selected due to the available information about sustainability and energy measures, either undertaken or planned. V&A Waterfront [26] and Torre Annunziata [27] were declining areas reconverted into commercial areas (like LMDV), although Torre Annunziata also has a residential area. Although transforming this UWF into a PED is not an explicit aim, there is nonetheless a commitment to improving efficiency in lighting and renewable energies generation (specifically PV) in both cases. Neither of them includes improvements to existing buildings, and even though water and waste management is outside the scope of this energy study, they play an essential role in both cases. It would be appropriate to consider the improvement possibilities in other UWFs. Schoonschip [28, 29] is a PED pilot in a residential waterfront with new buildings. The main characteristics are the high energy standards of the buildings, the onsite production with PV and thermal panes and the storage system. Zero Village Bergen [30] and Gruž [31] have adopted zero emission neighbourhood and zero energy perspectives, but their agenda has not yet been implemented.

Whilst detailed data exists on renewable energy generation and emission reductions strategies in ports (Table 3.1.1), in the case of waterfronts details are limited, since some of them still are in their planning stage. Although some measures have been implemented or planned, the literature review found no specific methods for planning and exploitation of the full potential of the UWF.

Table 3.1.2: UWFs measures.

	Renewable energy generation	Efficiency measures	Emissions plan	Electric mobility	Alternative fuels	References
V&A Waterfront	PV (2MW)	Cooling systems replacement. BMS (Building Management Systems) air conditioning control.	No plan. 35% reduction achieved in 2018	-	-	[26]
	Seawater cooling system (6MW)	95% common areas Light-emitting diode (LED), sensors				
		Net Zero GBCSA rating				
Torre Annunziata	PV (3,067,585 kWh/year)	LED (859.93 MWh/yr savings)	Absorption with trees (658,395 kg CO2/Year expected)	Cold ironing	-	[27]
Schoonship	516 PV panels with storage batteries, 60 thermal panels	30 heat pums, houses well isolated, showers with heat recovery system, green roofs, sustainable materials	-	Electric cars,cargo bikes and e-bikes	-	[28] [29]
Zero Village Bergen	PV panels, district heating	Replacement of building materials (lower emissions materials)	Zero emissions	Electric vehicles	Hydrogen	[30]
Gruž	PV panels, solar thermal, wind turbines	Bioclimatic design, post-isulation, galgae or greenhouse facades, heat pumps	Zero emissions	More use of public electric transportation	-	[31]

3.1.3 Contributions

There are great possibilities of generation in the outskirts, like ports, industrial parks, or isolated areas without great consumption; however, in cities there is usually high consumption but little generation capacity. This combination makes urban waterfronts a different typology from the energy point of view. Some UWFs implement actions to reduce their environmental impact, including renewable energy systems, more efficient air-conditioning systems with BMS technology [26], natural-based solutions, or cold ironing [27], among others. This paper addresses the characteristics of UWFs that set them apart from other spaces and their potential to become PEDs, aiming to understand if these urban spaces have the potential and how to become PEDs. Therefore, the aim is to prove that UWFs are urban districts that are particularly appropriate to become PEDs.

To prove the feasibility and how UWFs are appropriate to become PEDs, the study is applied to La Marina de València, the UWF of València, Spain. The proposal combines strategic planning for project management and the procedure for energy audits to design the optimal district configuration that aligns with the definition and objectives of a PED, depending on the specific characteristics of the studied UWF. A study of different scenarios is conducted in parallel to facilitate the decision-makers final selection for the UWF. Studying different strategies and a sensitivity analysis allows establishing a common pathway to achieve PEDs in UWF. The rest of the paper is structured as follows: Section 3.2 presents the method followed; section 3.3 explains the case study of La Marina de València (LMDV) in Spain; section 3.4 presents the results of the case study and the discussion and finally, section 3.5 concludes.

3.2 Materials and methods

In this section, a method for PEDs in UWFs that combines strategic project planning and energy audits is suggested to design the most optimal configuration that aligns with the definition and objectives of a PED, depending on the specific characteristics of the studied UWF. UWFs are extended areas close to the sea, making them suitable for several types of production with renewables, similar to ports. Furthermore, UWFs are contiguous to densely populated areas. Considering their location and potential for renewable energy production, UWFs appear as suitable locations for developing PEDs. For those reasons, a study for energy planning on urban waterfronts is conducted based mainly on strategic planning for project management [32] and the procedure for energy audits and aiming to develop PEDs in UWFs.

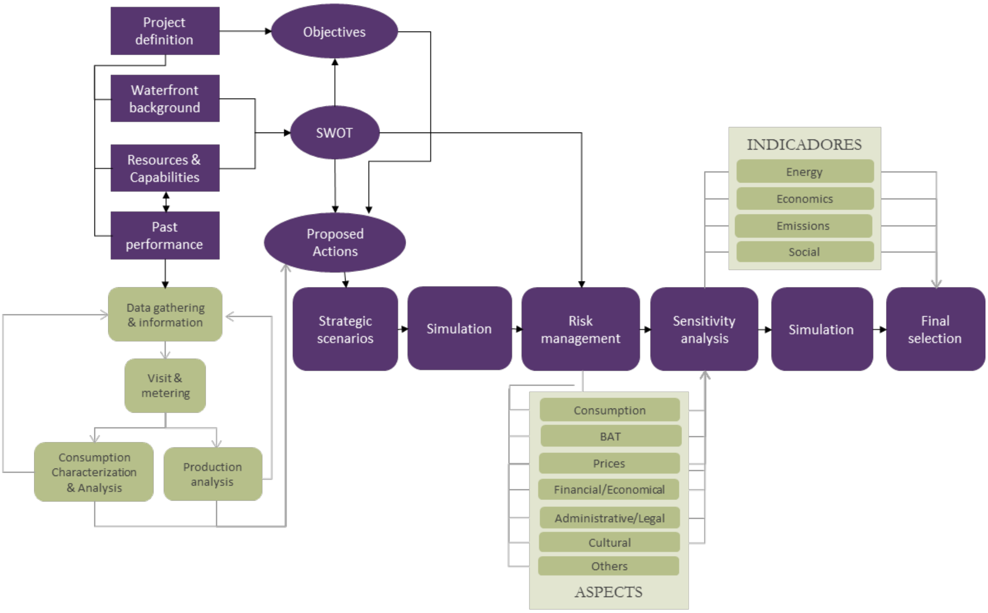

Figure 3.2.1: Methodology to plan PEDs in UWFs.

Based on strategic project planning, some of the methodology's main phases define the project and its objectives, the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, and the risk assessment [32]. Although these phases are shared with the strategic planning of projects, they have been defined more specifically for urban waterfronts' energy planning. The first step is the project definition, which involves the study of three main points:

- The UWF background, to better know the contexts, previous studies in energy and sustainability, and waterfront activities.
- The resources and capabilities of the area, in terms of energy resources, space availability, and possible barriers and possibilities to avoid them if any.
- The past performance analysis, regarding energy consumption and production.

An interview with the person responsible or involved entities and a literature review complete the first point. The two following points require a more elaborate procedure. The resources and capabilities study requires a review of the possible barriers and a more detailed process to identify and quantify renewable resources. The main aspects in which barriers might be found and should be assessed are space aspects as well as regulatory, financial, technological, social, or heritage aspects. Painuly et al. [33] identified barriers and policy implications of renewable energy technologies. Good et al. [34] studied the barriers and specific challenges for Energy Positive Neighbourhoods and elaborated recommendations. The resources available for energy planning will be all kinds of resources in the environment that can contribute to energy planning. These can be either operational or management resources or natural resources. Resources at the operational or management level will be detected in the context review phase, previous studies, and first interviews with the agents involved. Natural resources are the resources available for the generation of renewable energy. The availability of resources will be assessed first. A waterfront can be rich in various resources, such as solar radiation, wind, marine, geothermal or biomass; for each case, the availability must be assessed. Once the availability of resources is known, their potential for energy production at the location and their suitability related to energy demand must be assessed, considering their technical and economic feasibility. Section 3.2.1 defines this process and details the process of quantifying the resource and energy production potential for the available resources in the case study.

The next step for the project's definition is the past performance study, which gathers information about energy demand, consumption, and production (if any) and analyses it following the existing energy audits norm. Available information is collected, and installations are visited. If some information is not available and can be measured, the appropriate measurements are made. Data is continuously reviewed and completed in the analysis process as much as possible. If there is already energy production on-site, it will be determined from which sources, schedules, or conditions, and its power will be quantified. In the consumption characterisation, a distinction will be made between thermal and electrical demand. Moreover, information about consumption characteristics and hourly data for one year to carry out simulations will be collected.

Once this is completed, a SWOT analysis is carried out, taking the information from the background and the resources and capabilities. It provides an overview that allows the proposal of actions previous to the construction of strategic scenarios. The objectives of the project must be defined before proposing actions. The objectives of UWF correspond to the entities that comprise it; however, there may be an overall objective of increasing the waterfront's sustainability but no clear energy objectives in some cases, as has been found for two cases in the state of the art and the case study in this paper. In that case, considering the SWOT analysis previously carried out, several objectives can be proposed, and a strategic scenario can be generated for each one. Once the objectives have been defined, actions and measures are proposed to achieve them. From this point on, the different scenarios are defined and run in parallel; at the end, they are compared to select the most convenient option. To this end, a series of representative indicators should be selected to compare scenarios with each other and determine their suitability for the defined objectives. Indicators shall address emissions, economic and social criteria aligned with Sustainable Energy and Climate Action Plan (SECAP) and the PED definition. The scenario(s) definition involves a series of measures under its main objective. Having defined the strategic scenario(s), it is time to simulate. The software HOMER [35] is used for the simulations since it provides economic and technical results that will later be used to compare the scenarios. Once the first simulation is completed, the risks and the uncertainty variables must be identified.

After a literature review [33] and the SWOT, the risk analysis [36] must be conducted, and the uncertainty variables must be identified. For the risk analysis, first, the aspects with a risk of variation are identified: Consumption, Best Available Technology (BAT), prices, financial and economic, administrative and legal and cultural and social. Then, concerning these aspects, a series of risks and their consequences are detected for the case study. A qualitative risk analysis evaluates the priority of the identified risks using the probability of occurrence and the corresponding impact on the project. Then, contingency plans for risk management are proposed to reduce risk. A sensitivity analysis is then carried out by introducing variations in the variables corresponding to these aspects. The consequences of the variations introduced will be analysed to identify how they affect the optimal configurations for the strategic scenarios and the final selection for the project. The final strategy will follow different pathways depending on the evolution of uncertainty parameters; the sensitivity analysis will guide this decision-making. Some of the phases described above require a specific procedure to be developed. The following sections of this chapter explain these procedures.

3.2.1 Production analysis

This step consists of quantifying the renewable energy produced in the UWF, if any, and studying the production potential. The renewable energy resources to be considered are determined by analysing the available resources, available space for the installation of equipment and the production potential, and the maturity of the technology and its costs. First of all, the potential of different resources is assessed to dismiss low resource options. Also, some technologies might be rejected considering the type of demand to cover (thermal, electrical, or both). The suitable options for renewable energy production are finally selected, ensuring that the options are feasible. The feasibility is determinate by assessing the maturity and cost of the needed technologies and considering the capabilities and barriers identified.

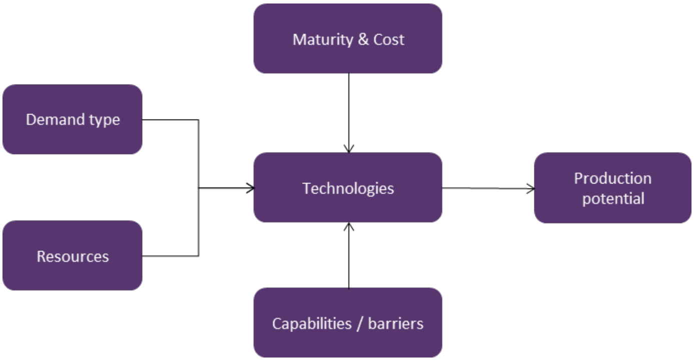

Figure 3.2.2: Renewable energy resources assessment.

UWFs can aggregate multiple renewable resources. Their proximity to the sea and their spatial characteristics contribute to significant renewable production potential. Resources can be provided to cover thermal demand through RES, such as geothermal, solar thermal, or biomass, or to cover electricity demand, such as PV, wind, or marine energy. This paper focuses on those used to cover the electricity demand of the case study, whereby the process of Figure 3.2.2, marine is discarded due to its high cost and lack of maturity in its applications with potential on the Mediterranean coasts [37].

3.2.1.1 Solar

It is necessary to identify the available spaces and obtain the power that could be installed regarding photovoltaic production. The district is examined for possible locations for installation, then the institutions involved are consulted to check the availability of such spaces for the installation of panels. Once available locations are checked, the installation's available areas are measured or obtained from cadastral information. Two cases of PV panel installations have been differentiated on existing rooftops and new structures in parking areas.

- Rooftops area

It has been decided to use the photovoltaic viewer supported by the Cátedra de Transición Energética Urbana [38] to assess rooftops. This tool obtains the roof area from cadastral information, which is reduced by defect by a factor of 70% to consider obstacles, railings, or others. The reduction factor of the photovoltaic viewer is calculated from a sample of buildings from Valencia city, similar to the one obtained by Arcos-Vargas et al. [39] for Seville (68%). The area/power ratio used by the photovoltaic viewer is 10 m^2/kWp. Thus, the peak power is obtained applying equation 3.2.1. Where A_{roof} is the rooftop area (m^2), f_{reduc}=0.7, $r_{area-power}$=0.1 kWp/m^2 and P is the peak power for that area (kWp).

$$P = A_{roof} f_{reduc} r_{area-power} \tag{3.2.1}$$

The solar radiation on the panels is estimated from an hourly Typical Meteorological Years (TMY) climate data file for Valencia provided by EnergyPlus [40], and a radiation isotropic model. The model considers shadows cast by all the buildings or obstacles adjacent within a radius of 200 m from a representative point on the roof. The shadows are calculated from Light Detection and Ranging (LIDAR) data and cadastral data.

- New structures area

In the zones without buildings where the installation of panels is proposed, the maximum number of panels and the power are obtained as follows. First, the available area is measured. Then, knowing the space's width and length, the structures' slope angle to install the PV panels and the panels' power is obtained in order to discover the total power for each area. The equations used for each area are:

$$N_p = N_L N_W \tag{3.2.2}$$

$$N_L \approx \frac{L}{L_p} \tag{3.2.3}$$

$$N_W \approx \frac{\frac{W}{cos(\alpha)}}{W_p} \tag{3.2.4}$$

$$P = N_p P_p \tag{3.2.5}$$

Where N_L and N_W are the maximum number of panels to install, L is the length and W the width of the available area respectively, L_p and is W_p for the panel dimensions, α the angle of inclination of the structure, P_p the panel peak power and P the peak power for that area.

The radiation data is obtained from the Photovoltaic Geographical Information System (PVGIS) website [41]. Weighted average values are used for the azimuth and the slope of the panels (equations 3.2.6 and 3.2.7) to obtain the PVGIS radiation and carry on the simulations since it will be considered as a single installation for the scenario simulations. Where ϕ is the weighted average angle, ϕ_i is the angle and rp_i is the ratio of the power of the installations with the angle ϕ_i to the total power.

$$\phi = \sum(\phi_i rp_i) \tag{3.2.6}$$

$$rp_i = \frac{P_{\phi_i}}{P_{tot}} \tag{3.2.7}$$

- Shadows

The shadow pattern will be projected onto the Sun-path diagram. The shadow pattern is obtained for a central point of the roof. The distance and height of the obstacles' vertices are obtained with respect to this point. The solar elevation angle (β) and azimuth (α) are obtained for each vertex of the obstacle employing trigonometric relations. The shadow pattern is then defined and can be projected onto the diagram. With the pattern of shadows overlaid on the diagram, it can be seen in which months and hours the obstacle prevents radiation reaching the point on the roof being analysed. Then, the realistic hourly radiation data generated for the entire year before is modified, setting the hours at which shadows occur to zero. This procedure is done for as many roofs or points as required by the geometry of the buildings.

Finally, weighted average radiation is obtained. A different coefficient is obtained for each zone with shadows and another one for the area without shadows. The weighting is made with respect to the installed power, with the coefficient for each zone being the power installed in that zone divided by the total installed power.

- Connection to consumption points

Although a single photovoltaic installation linked to the total demand will be considered, it should be noticed that this is a simplification. An additional study is needed to link the PV production facilities with different consumption points, adapt schedules, power, and consider the current legislative framework. In Spain, self-consumption installations are currently defined by RD 244/2019 [42], which specifies that the distance between production and consumption point must not exceed 500 metres.

Mapping is conducted connecting the proposed PV generation points. According to the current regulation, the map shows the minimum radius circumference between generation and supply for each generation point. The consumption points within this area are established as options. Then, the installations' peak power is compared with the different consumptions and schedules, so the most suitable combinations are established. The annual consumption of each point is also compared with the estimated annual production of the photovoltaic viewer.

3.2.1.2 Wind

The wind data have been obtained by interpolating Energy Plus and the Institute for Diversification and Saving of Energy (IDAE) data. Energy Plus provides average hourly wind speeds for each month for the location. The IDAE's data is from 2018 when its wind atlas [43] was still available. The information provided is for a more specific location, with annual, seasonal, and wind direction values.

With the hourly data of average speeds for each month obtained interpolating, it is possible to establish if the resource will be enough to produce energy with a wind turbine. For the simulations, hourly data will be used. The wind turbine's best orientation is determined by obtaining the wind roses for frequency, speed, power, and energy. The power and energy for each orientation are calculated with the expressions:

$$P_j = \frac{1}{2}\rho\frac{\phi D^2}{4}v_j^3 \tag{3.2.8}$$

$$E_j = f_j P_j h_{yr} \tag{3.2.9}$$

Where j is the wind direction, ρ is the air density, which is variable depending on the height above the sea, D is the wind turbine's rotor diameter, and v is the average speed for each direction. E is the energy, P the power, f the frequency percentage and h_{yr}=8,760 hours in a year. After evaluating the wind resource, the location suitable for installation is selected. Once the location is known, the maximum number of wind turbines is determined by taking measurements in the available location and following the inequation below, where d is the distance between wind turbines and D the rotor diameter.

$$d \geq 3D \tag{3.2.10}$$

3.2.2 Indicators

Four indicators have been selected to assess the results of each scenario, these consider economic, environmental, and energy variables. Social indicators have been left out in the simplification applied to the case study, but they are another aspect to be considered in PEDs. The selected indicators are four outputs of HOMER:

- Net present value (NPV) or present worth: the difference between the present value of cash inflows and the present value of cash outflows over a period of time (€). The NPV of each scenario is calculated with the following equations: the difference between the present value of cash inflows and the present value of cash outflows over a period of time (€). The NPV of each scenario is calculated with the following equations:

$$NPV = NPC_{scenario} - NPC_{ini} \tag{3.2.11}$$

$$NPC = \frac{C}{(1+i)^n} - \frac{R}{(1+i)^n} \tag{3.2.12}$$

Where C is the costs of installing and operating the component over the project lifetime, R revenues that it earns over the project lifetime, i the real interest rate and n the lifetime. $NPC_{scenario}$ is the NPC of the whole system for each scenario, and NPC_{ini} for the current system.

- Levelized cost of energy (LCOE): average cost per kWh of useful electrical energy produced by the system (€ /kWh).

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{3.2.13}$$

Where $C_{ann,tot}$ is the total annualised cost of the system (€ /yr). The total net present cost times the capital recovery factor. E_{served} is the total electrical load served (kWh/yr), the total amount of energy that went towards serving the primary and deferrable loads during the year, plus the amount of energy sold to the grid.

- Renewable energy production: the total amount of electrical energy produced annually by the renewable components of the power system (kWh/yr).

- CO_2 grid emissions:

$$AnnualCO_2savings = \sum_{t=1}^{t=8760} E_{purch,c\_t} fco_2\_t - (E_{purch,sc\_t} - E_{sold,sc\_t}) fco_2\_t \tag{3.2.14}$$

Where E_{purch_t} is the grid purchases at hour t from the current systems (E_{purch,c_t}) or the strategic scenario (E_{purch,sc_t}), E_{sold_t} the grid sales at hour t and fco_2_t the emission factor (g/kWh) at the correspondent hour. $fco_2\_\ t$ is obtained for the year 2019 (the same year as consumption data) from Red Eléctrica de España (REE) website for the entire year.

3.3 Case Study: La Marina de València

València is a city located on the east coast of Spain. It is situated on the banks of the Turia, fronting the Gulf of València on the Mediterranean Sea. It has a population of 789,744 inhabitants and a surface area of 134.65 km^2. València has a hot-summer Mediterranean climate with mild winters and hot, dry summers. The average annual temperature is 18.4 °C. August is the warmest month, with average maximum temperatures of 30-31 °C and minimum temperatures of 21-23 °C. The daily temperature range is low due to the maritime influence: around 9 °C on average. Also, the average annual humidity is relatively high (about 65%) and with slight variation throughout the year due to the sea's influence.

La Marina de València (LMDV) is in a UWF in the city of Valencia. It was initially part of the city's port, but the preparations to host the 32nd America's Cup led to the separation of La Marina de València from the rest of the commercial port in the early 2000s. Between 2007 and 2012, La Marina de València hosted two editions of the America's Cup and the Formula 1 Grand Prix, which led to the fast development of its infrastructure and debt accumulation. After that, many of these infrastructures built to host the two events were left without a defined use. Nowadays, space is increasingly being retrieved for the citizens. It is managed by Consortium 2007, and its current priorities are innovation and sustainability. These new priorities but with the lack of specific objectives are the reason why this UWF was selected as the case study.

Figure 3.3.1: LMDV map.

After analysing its energy consumption, it was found that this is mainly due to electricity demand and that thermal energy consumption is negligible compared to this demand applying the Pareto principle. The consumption of some small boilers for Domestic Hot Water (DHW) compared to the consumption of 850 dock pedestals from 16A to 630A, 479 kW for pumps working intermittently and not all simultaneously, and total power of 229 kW for public lighting makes the boilers negligible. It will be considered a measure of efficiency to change the sodium or mercury vapour discharge systems to LED technology.

For the consumption characterisation and analysis, monthly consumption electricity data has been collected from 25 electricity supply points dependent on Consorci València 2007, of which 17 have been analysed in more detail with the hourly load curves for the whole year. The consumption of LMDV for 2019 was 7,001 MWh/year. The main consumption points are concentrated in mooring areas and the lighting. There are consumption points with higher consumption than others, some with more diurnal consumption, which will be more suitable for the PV installations, and others with more nocturnal consumption, depending on the type of demands linked to them. However, the overall curve is relatively flat, with higher consumption at night (Figure 3.3.2). Average consumption on Saturdays and Sundays is higher than the rest of the week. Consumption does not vary much throughout the year, being slightly higher from June to November.

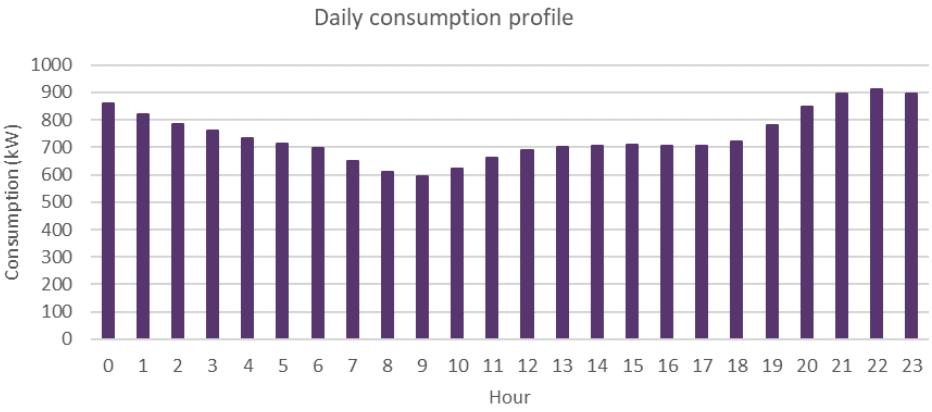

Figure 3.3.2: Daily consumption profile.

For the analysis conducted, an estimation of the electricity demand produced by Electric Vehicles (EV) charging points has been included in the total electricity demand considering the forecast of 16% of the vehicle park for 2030 [43] and information about the parking places and schedules in LMDV. With the estimated curve for EVs, the annual consumption will increase by 1,849 MWh, 26.5% more than 2019 consumption.

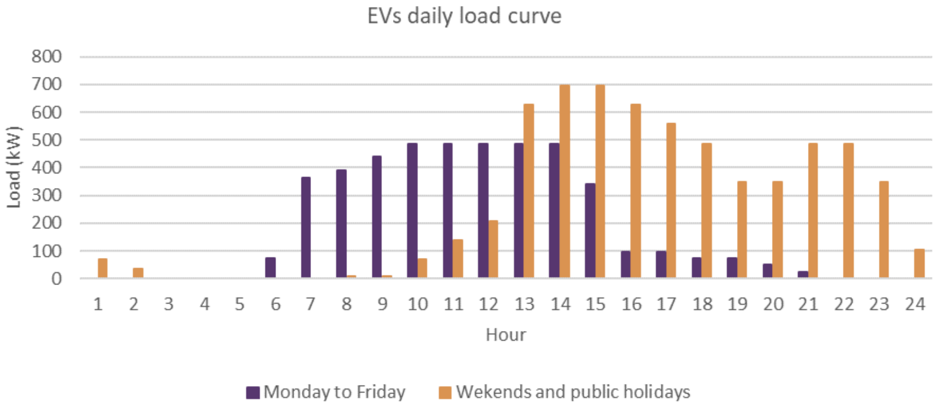

Figure 3.3.3: EVs daily load curve.

For the production analysis no renewable production has yet been introduced in LMDV. For the potential of production, due to the demand's main electric character, technologies to produce electricity from renewable sources are considered. The proximity to the Mediterranean Sea and the low level of sea roughness and availability of space away from towns make electricity production by wind turbines feasible. The climatic conditions and the wide availability of space make the production using PV panels viable. Besides, both technologies are mature and economically competitive. Those are the technologies considered for energy production in situ. Moreover, using a storage system with Li-ion batteries will be considered. The prices of the equipment under consideration are shown in Annex 1. Since these devices have a greater economy of scale, equations as a function of power have been obtained to approximate the price in € per kW for inverters and per kWh for batteries from several devices of different power and capacity. The Operation and Maintenance (OM) cost for the inverters is 16 € /kW and 3 € /kWh for the batteries.

For the LMDV case study, three strategic scenarios are proposed to achieve a different target since no specific target was previously specified. The strategic scenarios are:

- **Maximum energy production (P)** from renewable sources in LMDV: Become a driving force in renewable energy in the area by exploiting its full potential.
- **Maximum renewable autarchy (A)**: Self-sufficiency, own renewable energy supply for LMDV independent of the electricity grid and any other external supply.
- **Minimum cost (C):** efficient energy management leading to minimisation of energy costs.

The project's lifetime is considered to be ten years, within which time it is intended to meet the objective of making LMDV a sustainable area. For LMDV, the sensitivity analysis has been carried out using 25% upward and downward variations in the consumption and the electricity price. The presentation of results nomenclature contains a letter corresponding to the strategic scenario followed by a number: 0 for scenarios without changes, 1 or 2 for increase or decrease in consumption respectively, and 3 or 4 for increase or decrease in electricity prices and 5 and 6 for increase or decrease in equipment price. Finally, the worst and best combinations for the different scenarios are simulated. The worst combination, labelled 7, assumes an increase in consumption and equipment and electricity prices simultaneously. The best combination is the opposite: consumption drop and equipment and electricity price drop (number 8).

3.4 Results and discussion

Once the scenarios have been defined, the first set of simulations is carried out to establish the proposals that will make up the scenarios. A sensitivity analysis is then carried out to review the scenarios and decide whether to apply modifications to them. Finally, the three scenarios are compared to establish the most convenient for forming a PED in LMDV. Each scenario includes integrating PV panels and wind turbines to a different extent depending on the results obtained in the simulations and each scenario's main objective. Besides, all include improving

Table 3.4.1: Results of the switch to LED technology.

	Current	LED	Savings
Investment (€)	-	11,762	-
Payback (yrs)	-	2.4	-
Power (kW)	229.25	122.09	107.16
Consumption (MWh/yr)	1,170.78	626.51	547.27
Cost (€ /yr)	100,817	53,692	47,126
Emissions (tCO_2)	134.64	71.7	62.94

lighting efficiency by switching to LED technology. The lighting change represents a total cost of 114,762 € and saves 7.9% of energy and 62.94 tCO_2 emissions per year. The payback of this efficiency measure is 2.4 years.

After the first simulations, the configurations and the investment cost obtained for each scenario are shown in Table 3.4.2, while Figure 3.4.1 shows the simulations' main results. In the maximum production scenario (P0), the maximum available PV and wind power will be installed. For the maximum autarchy scenario (A0), the option with the minimum number of batteries has been selected, as batteries exponentially increase the project costs. In the minimum cost scenario (C0), the configuration selected is the one that achieves the lowest LCOE at 6.1 cents € /kWh.

The three strategic scenarios are technically feasible and have net-zero emissions and a positive energy balance annually, but each has advantages and disadvantages. For P0 and C0 scenarios, the most feasible configurations do not include batteries. It is not a feasible option from the economic point of view but implies independence from the grid. C0 has a significantly lower cost than P0 and a higher NPV, while A0 has a negative NPV. In contrast, P0 means higher renewable energy production to sell to the grid. Both P0 and C0 reduce CO_2 emissions from the electricity grid, due to the discharge of clean energy into the grid. Savings in grid emissions are significantly higher in P0.

Table 3.4.2: Strategic scenarios configuration and investment cost.

SCENARIO	Installed power (MW)			Inverter	Batteries	Investment cost (€)
	PV	Wind	TOTAL	(MW)	capacity (kWh)	
P0	2.76	4	6.76	2.48	0	7,153,813
A0	2.76	4	6.76	2.48	5,240	8,072,946
C0	2.76	2	4.76	2.48	0	4,539,813

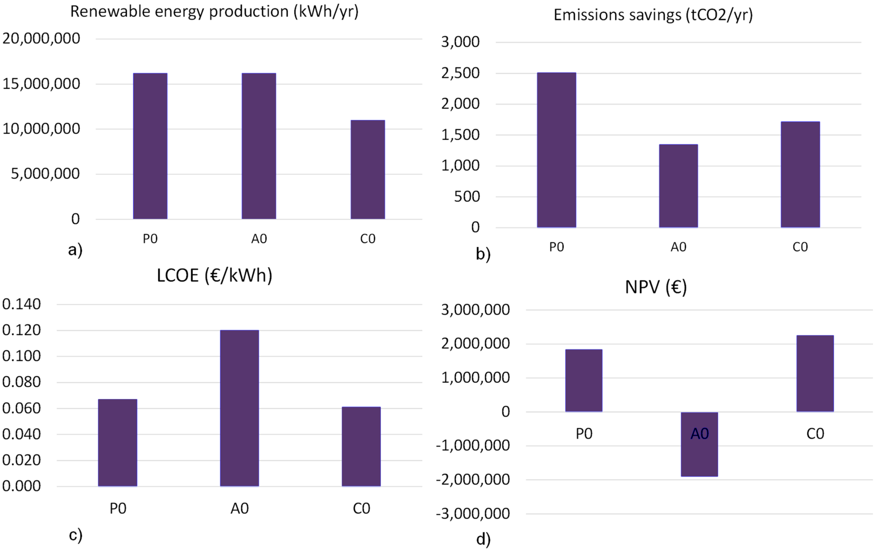

Figure 3.4.1: Strategic scenarios results.

a) Renewable energy production of the strategic scenarios, b) CO_2 emissions savings of the strategic scenarios, c) LCOE of the strategic scenarios, d) NPV of the strategic scenarios.

In the sensitivity analysis of the scenarios, the parameters with higher uncertainty, consumption, electricity price and equipment price, are selected to study the effect of its variation for the three strategic scenarios. The variations for those parameters hereby presented are ±25%.

3.4.1 Maximum energy production

P scenarios configuration is always the same, since the maximum production target leads to installing the maximum power capacity available (see Table 3.4.3). The rise and drop of consumption (P1 and P2) affect the emissions savings. An increase in consumption results in lower grid emissions savings and vice versa. LCOE and NPV are affected by both changes in consumption and electricity prices. Reducing consumption (P2) increases the LCOE and significantly increases the NPV. The opposite effect occurs when consumption rises (P1). The increase in the price of electricity (P3) or the equipment price (P5) decreases the NPV, and the rise in the price increases it, with an effect weaker than those produced by consumption variations or electricity prices, but higher for equipment prices. The opposite effect occurs when prices drop (P4 and P6). For P7 (worst combination: consumption and price rise) and P8 (best combination: consumption and prices drop), emissions are the same as P1 and P2, as they have the same energy consumption and production. In P7, as in P5, the increase of electricity prices affects the LCOE negatively. The opposite occurs with P5 and P8. P7 and P8 have the worst and the best NPV result, respectively, with P7 being the only case with negative NPV and therefore economically unviable. This occurs because it is the worst and best combination of variations in the parameters. The results for the sensitivity analysis of the maximum energy production scenario also show that in all cases LMDV will be a PED (net-zero emissions and a positive energy balance on an annual basis).

Table 3.4.3: Renewable energy production of max. production sensitivity analysis configurations.

SCENARIO	Installed power (MW)			Inverter	Batteries	Investment cost (€)
	PV	Wind	TOTAL	(MW)	capacity (kWh)	
P0, P1, P2, P3, P4	2.76	4	6.76	2.48	0	7,174,809
P5, P7	2.76	4	6.76	2.48	0	8,939,820
P6, P8	2.76	4	6.76	2.48	0	5,409,797

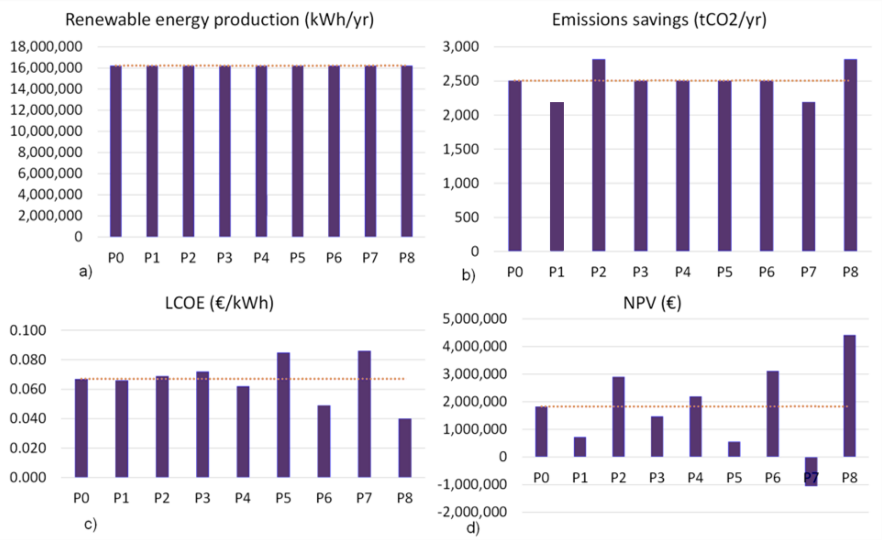

Figure 3.4.2: Maximum production variations.

a) Renewable energy production of max. production variations, b) CO_2 emissions savings of max. production variations, c) LCOE of max. production variations, d) NPV of max. production variations..

3.4.2 Maximum renewable autarchy

The maximum power would be installed for the maximum autarchy scenarios, excluding the consumption drop case (A2). Thus, production would be the maximum as in P scenarios. A2 is the only case that reduces the PV installed power, increases the storage system slightly, and lowers the investment cost. Nevertheless, in A2, it must be ensured that the reduction in power consumption is applied uniformly. Suppose e.g., the reduction in consumption occurs during the dark hours but not during the daylight hours. In that case, the configuration described above may no longer be optimal, and the initial configuration (A0) may be preferred. However, increasing consumption (A1) would require a more significant storage capacity to guarantee the supply. The LCOE remains high compared to P scenarios, although it decreases in A8, A2, A6, and A1, with A2 and A8 the only cases with a positive NPV. Given the independence of the grid, the variations in the electricity price (A3 and A4) do not affect either the configuration or the results compared to A0. Without the grid and the economic compensation and having to install batteries, which are expensive, the best scenario is if consumption is reduced (A2) due to the reduction of the power installed and, therefore, investment reduction. A7 and A8 give the worst and the best result for NPV, but not for energy production and LCOE. A7 increases the price of equipment and consumption. As can be seen in Figure 3.4.3 c), in the case of increased consumption (A1), the LCOE is favoured compared to the base case (A0), due to increased use of on-site renewable energy, due to an increase in the storage system. In the case of increased equipment prices (A5), the LCOE is negatively affected. Therefore, A7 is, in this aspect, an intermediate case between A1 and A5. A PED will be achieved for all the scenarios resulting from the sensitivity analysis of this strategic scenario.

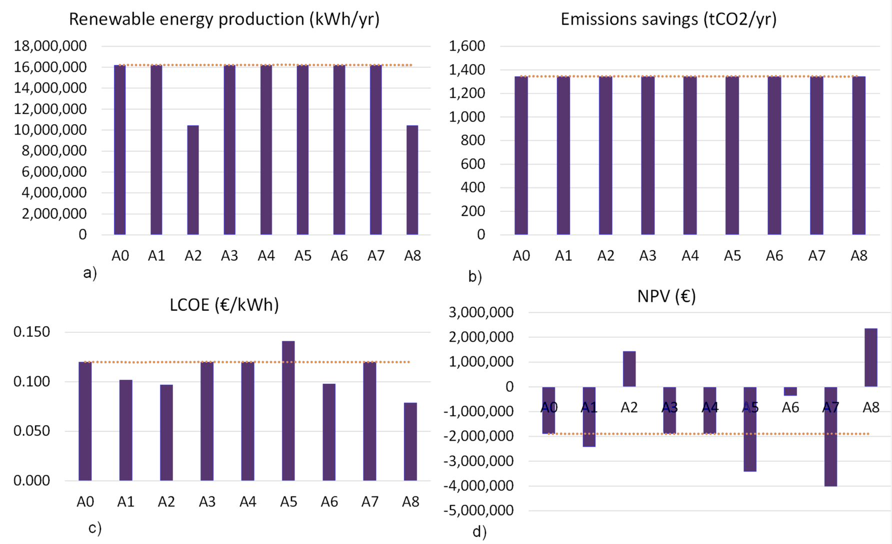

Figure 3.4.3: Maximum autarchy variations.

a) Renewable energy production of max. autarchy variations. b) CO_2 emissions savings of max. autarchy variations. c) LCOE of max. autarchy variations. d) NPV of max. autarchy variations.

Table 3.4.4: Renewable energy production of max. production sensitivity analysis configurations.

SCENARIO	Installed power (MW)			Inverter	Batteries	Investment cost (€)
	PV	Wind	TOTAL	(MW)	capacity (kWh)	
A0, A3, A4	2.76	4	6.76	2.48	5,240	8,072,946
A1	2.76	4	6.76	2.48	13,100	8,600,426
A2	2.5	4	6.5	2.48	5,502	5,054,522
A5	2.76	4	6.76	2.48	5,240	10,088,709
A6	2.76	4	6.76	2.48	5,240	6,099,129
A7	2.76	4	6.76	2.48	13,100	10,721,805
A8	2.50	2	4.50	2.48	4,912	3,790,619

3.4.3 Minimum cost

The optimal configuration of the minimum cost case changes with respect to C0 when consumption or electricity price drops (C2, C4 and C5), resulting in the removal of wind energy generation. In the case of an equipment price drop (C6), the optimal configuration is installing the maximum available. The minimum LCOE is obtained in C8 followed by C6 and C4, since C8 is a combination of all cases where the LCOE falls below C0 (C2, C4 and C6). The lowest energy production is in C2, C4 and C5 since the power installed is lower. Thus, the emissions savings are lower too. In C2, the consumption is also reduced; thus, there are more emission savings. If the equipment price is reduced (C6), the best results are obtained in production and CO2 savings because the maximum power is installed. In C8, the installed power is reduced to improve the LCOE and the NPV to the best values. C7, the combination of an increase in consumption and prices, is the only case with a negative NPV. Unlike the other strategic scenarios, the variations of the sensitivity analysis for the minimum cost scenario show that a PED will not always be achieved. For scenarios C2, C4, and C5, with less installed power (no wind turbines), therefore less production, the net-zero emissions, and the positive energy balance are not achieved.

Table 3.4.5: Minimum cost sensitivity analysis configurations.

SCENARIO	**Installed power (MW)**			**Inverter**	**Batteries**	**Investment cost (€)**
	PV	**Wind**	**TOTAL**	**(MW)**	**capacity (kWh)**	
C0, C1, C3	2.76	2	4.76	2.48	0	4,560,809
C2, C4	2.76	0	2.76	2.48	0	1,946,809
C5	2.76	0	2.76	2.48	0	2,404,821
C6	2.76	4	6.76	2.48	0	5,409,797
C7	2.76	2	4.76	2.48	0	5,672,321
C8	2.76	2	4.76	2.48	0	3,449,297

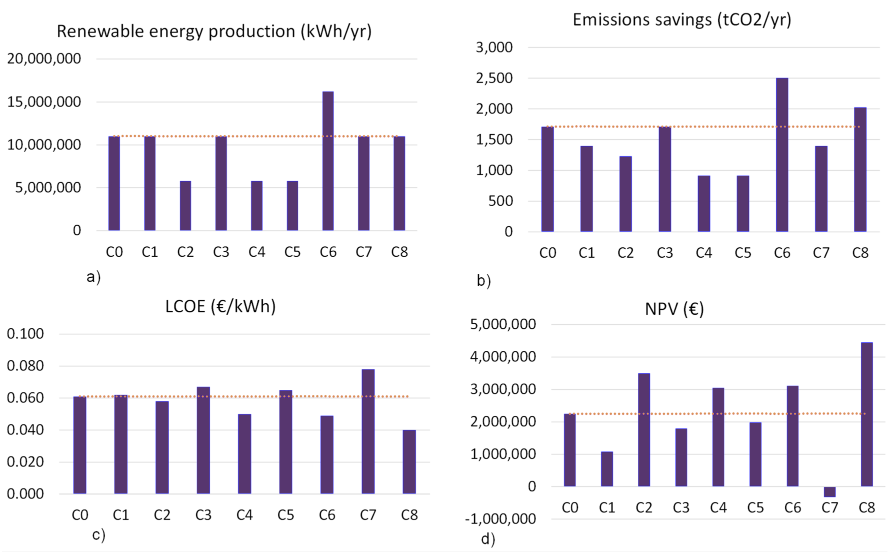

Figure 3.4.4: Minimum cost variations.

a) Renewable energy production of min, cost variations. b) CO_2 emissions savings of min. cost variations. c) LCOE of min, cost variations. d) NPV of min, cost variations autarchy variations.

3.4.4 Possible pathways

Figure 3.4.5 represents nine alternatives from the sensitivity analysis for the three strategic scenarios. PV power is in magenta colour, wind power in blue, and the rest left to reach the maximum available power in grey. All the alternatives include PV; indeed, only two do not suggest to install the maximum PV power (2.76) and suggest 2.5 MW instead; both are from the maximum autarchy strategic scenario. Only three alternatives do not include wind power; all three are from the minimum cost strategic scenario. Those three alternatives correspond to a consumption or electricity price drop or an equipment price rise. Most of the alternatives (18) will include 4 MW of wind, but six will include only 2 MW. The reduction in consumption is favourable in all three strategic scenarios, emphasising the importance of implementing efficiency measures (LED). The decrease in the price of electricity and equipment also has a positive effect, as expected. However, an increase in consumption due to increased activity in LMDV would worsen the alternatives. Therefore, further investigation of energy efficiency improvement options is recommended for future studies.

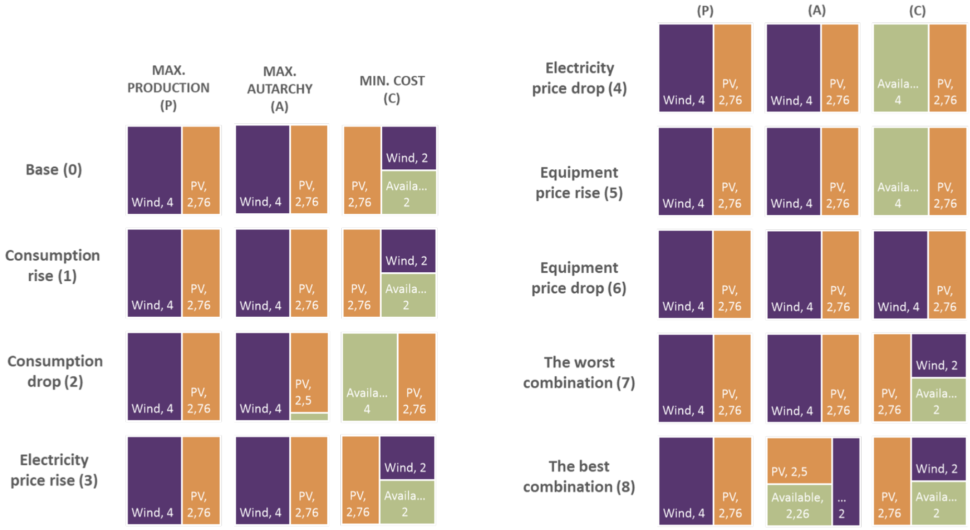

Figure 3.4.5: PV and Wind power (MW) for each sensitivity analysis alternative.

These results show that the final strategy will follow different pathways depending on the evolution of the uncertainty parameters analysed. The strategy of maximum autarchy is discarded since it is economically viable only on the assumption of consumption reduction (A2) or consumption reduction and equipment prices drop (A8) (Figure 3.4.3). Furthermore, given the changing nature of consumption in LMDV due to occasional events, independence from the grid is a complex option that could compromise the continuity of supply. The decision is between the strategy of maximum production and minimum cost. All the alternatives from the sensitivity analysis have two common points, the switch to LED and at least 2.5 MWp of photovoltaic, 2.76 MWp if discarding the strategy of maximum autarchy. This ensures the suitability and relevance of these two proposals for LMDV despite the strategy and changes that may occur in the future. Both switching to LED and photovoltaics can be implemented progressively, avoiding a significant investment all at once. Priority should be given first to the switch to LED as an efficiency-enhancing measure and then to the installation of photovoltaics. Once those have been progressively completed, the installation of wind turbines should be considered. From this point onwards, depending on the investment capacity, it would be decided whether to follow a strategy of maximum production (higher investments) or minimum cost (lower investments). Once the strategy has been decided, the evolution of prices and consumption should be assessed in order to determine the wind power capacity to be installed. If the investment capacity is sufficient and maximum production is chosen, 4 MW of wind power will be installed. If cost reduction is chosen and the minimum cost strategy is followed, it will depend on the evolution of electricity consumption, electricity prices, and equipment prices (Table 3.4.5).

The differences between the maximum and minimum cost strategic scenarios are blurred when gradually approaching the energy strategy change. For the same price and consumption evolution, the minimum cost strategy always implies less power to install and less investment, except if the price of the equipment falls. In that case, the maximum production scenario and the minimum cost scenario match. In any case, the lower power configurations of the strategic minimum cost scenario always allow the evolution to the maximum production scenario by increasing the installed power up to the maximum possible. Either by installing one 2 MW wind turbine or two, depending on the case.

3.4.5 Discussion

Although the three strategic scenarios are feasible, the sensitivity analysis points out some differences between them. The sensitivity analysis determines that the minimum cost and the maximum autarchy scenarios are the most influenced by variations in the sensitive parameters. However, independently of the strategy ultimately defined, all the scenarios share the lighting change and a minimum of 2.5 MW of PV installations, 2.76 MW if discarding the maximum autarchy scenario.

The difference between the configurations of one strategy or another is related to installing wind turbines or batteries but rarely affects PV's installation power. Furthermore, an advantage of the PV installations is the possibility of doing it progressively, avoiding big investments in short periods. At this point, depending on the evolution of uncertainty parameters, infrastructure planners could decide how much wind power to install, bearing in mind that not installing wind turbines means not achieving a PED. It would be necessary to install at least one wind turbine to achieve the PED target.

Working with several strategic scenarios in parallel facilitates the decision-makers' final selection. The sensitivity analysis shows how uncertainty affects scenarios and which are more affected. Moreover, the study of different strategic scenarios allows the establishing of a solid base of measures for the UWF common to all of them. The inclusion of further measures is dependent on the selected strategy. Still, the shared measures are the starting point for any energy strategy in the UWF, which are potential and unique candidates to become PED in urban areas. The energy planning for UWFs can be compared with the energy planning of islands conducted by Mimica et al. [44]. The main difference between islands and UWFs lies in costs, since the most cost-effective solution on the mainland could be significantly more expensive on the islands. Furthermore, the PED approach is better suited for UWFs due to the proximity to contiguous urban areas with which the UWF can exchange the surplus of energy.

Due to the availability of space and resources UWFs present a great opportunity for large generation in cities, enabling a positive energy balance to be achieved. Thus, the potential of UWF lies on the focus on renewable energy potential and use. Whereas in other areas of the city, such as residential districts, the focus lies on a higher penetration of energy and CO_2 saving measures. Future research could analyse the impact of UWFs on the whole city. To that end, the SDEWES Index [45], with which Valencia has been benchmarked with other 120 cities, could be a starting point. The SDEWES Index measures with different indicators 7 dimensions of the sustainable development. The potential and contribution of the UWF would be measured in the 7 dimensions comparing with the values for the whole city.

3.5 Conclusions

This paper presents different scenarios to achieve PED in a UWF. A method is applied based on data gathering, demand analysis, a study of the feasible renewable energy capacity, and techno-economic simulation of the different scenarios. The approach is validated in the UWF of the city of València with three scenarios, maximum renewable generation, autarchy, and minimum cost. UWFs are particularly interesting districts of cities, as in contrast to most urban districts, they have large spaces for renewable generation. The results show that a PED is achievable in LMDV, with only three exceptions among all the scenarios resulting from the sensitivity analysis of the minimum cost scenario. Moreover, all scenarios show a common path for the district. A combination of demand efficiency measures (LED lighting) and Solar PV installation is common in any scenario that aims to achieve a PED or improve the energy performance of the UWF.

The proposed method considers the context, the possibilities, and the expected evolution of the UWF. Based on the current state and the SWOT analysis, a prediction of future demand is made, barriers are also considered, and risk and sensitivity analyses of the proposals, consumption and prices are carried out. In addition to all this, a parallel study of several strategic scenarios is proposed to analyse the possible pathways and then establish the most appropriate one based on the indicators' results. Considering several scenarios parallel and carrying out a sensitivity analysis makes it easier to decide which scenario is the most suitable and which is the order of priorities within each scenario. Furthermore, the feasible measures in all scenarios are consolidated as a starting point in the energy strategy.

UWFs are districts with particularities such as greater availability of space and resources than other city districts. This makes them areas of interest for developing PEDs, a key strategy in the decarbonisation of cities. Although some UWFs have implemented energy efficiency and production measures, the PED approach in UWFs is still in its infancy. In addition to the novelty of the PED approach in UWFs, there is, in general, a difficulty for policymakers and competent authorities in PED planning. The decision of which measures to implement, whether efficiency or generation measures, must be based on energy demand and resource availability. But future barriers and predictions of consumption, prices, and technology evolution will also affect the suitability of the scenario and solutions to achieve a PED.

In sum, if cities are going to be a central effort in decarbonising societies, UWFs present a critical and ideal location to become a renewable generation oasis inside cities. While efforts in cities will concentrate on smaller self-generation facilities, energy efficiency measures, and the electrification of transport, the opportunity of larger scale generation must be considered. Future studies should analyse the global impact and potential of UWFs not only as single districts but as contributors to cities, and the particularities and impacts of real scale projects.

CRediT authorship contribution statement

Isabel Aparisi-Cerdá: Methodology, Software, Data Curation, Writing - original draft. David Ribó-Pérez: Conceptualisation, Methodology, Supervision, Writing- review & editing. Iván Cuesta-Fernandez: Supervision, Writing- review & editing. Tomás Gómez-Navarro: Methodology, Writing - review & editing, Supervision.

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3.6 Appendix

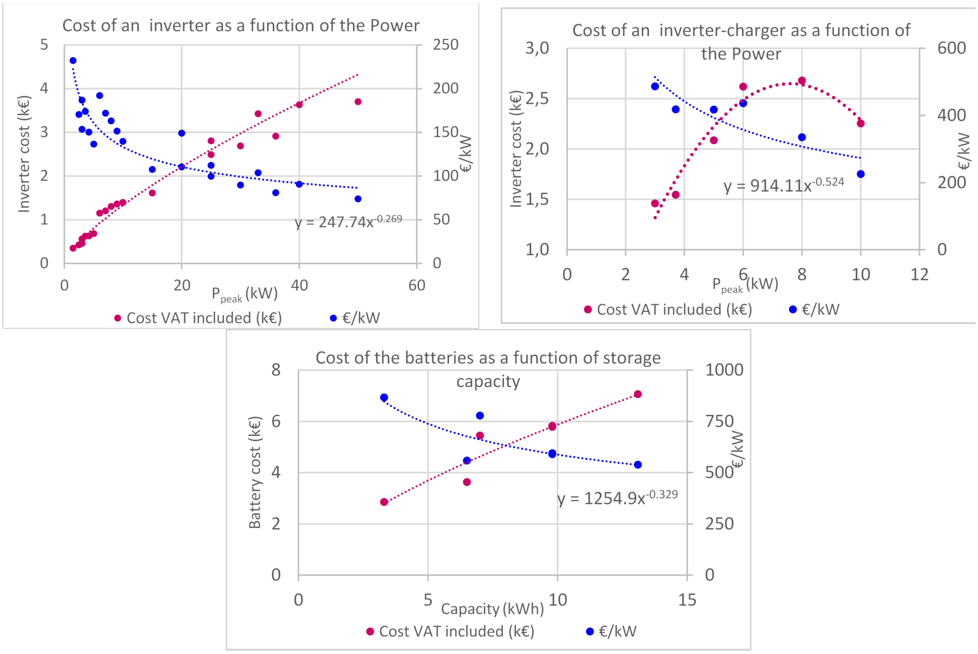

Figure 3.6.1: Cost of inverters, inverter-chargers and batteries.

Table 3.6.1: Equipment prices.

	PV panels (400W)	Coplanar structure	Sloping structure	Parking structure	Panels O&M	Wind turbines (2MW)	Wind turbines O&M
Cost(€ /kW)	408	77.5	142.5	454.6	16	1150	45

The O&M cost for the inverters is 16 € /kW and 3 € /kWh for the batteries.

Table 3.6.2: Equipment prices.

Period	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
Power Cost (€ /kW/day)	0.107	0.054	0.039	0.039	0.039	0.018
Energy Cost (€ /kWh)	0.109	0.096	0.085	0.077	0.074	0.064

Chapter 4

Assessing gender and climate objectives interactions in urban decarbonisation policies

Assessing gender and climate objectives interactions in urban decarbonisation policies

[5] *Isabel Aparisi-Cerdá, David Ribó-Pérez, Júlia Gomar-Pascual, Julia Pineda-Soler, Rocío Poveda-Bautista, Mónica García-Melón. "Assessing gender and climate objectives interactions in urban decarbonisation policies." Renewable and Sustainable Energy Reviews, vol. 189, pp. 113927-113940, 2024*

Abstract

Gender studies have highlighted how policies and actions that are not drafted and planned with a gender perspective tend to produce a gender bias. Climate policies are not an exception. Measures to mitigate and adapt cities to climate change might lead to undesired outcomes regarding gender equality or, in contrast, may help to improve equality. Ideally, cities should prioritise actions that aim to reduce their carbon footprint but also help promote gender equality. The aim is to facilitate the inclusion of gender perspective in the 100 Climate-Neutral and Smart Cities by 2030 European Mission. We propose a Multicriteria Decision-Making Method to assess urban policies and relate them to climate and gender criteria. We describe urban decarbonisation policies with non-negative gender outcomes and compare their impact when using climate and gender criteria. The objective is to analyse how the prioritisation of actions varies from different perspectives: one taking into account the field of expertise of the different experts and the other taking into account the different typologies of criteria separately. A DEMATEL-ANP technique is used to determine how policies contribute to climate action and gender equality. Experts in different areas and city planning respond to the DEMATEL-ANP model by comparing and relating criteria and actions. The results show which policies have a significant potential to reduce cities' carbon footprint and increase gender equality. Prioritisation of policies changes when only gender criteria or climate criteria are considered. Regarding the former, it can be concluded that gender criteria will contribute to closing the gender gap while having a widening impact on decarbonisation. Nevertheless, including gender criteria is not enough to avoid bias, and multidisciplinary teams must participate in the decision-making process.

Keywords

Gender Perspective; Climate Policy; Urban Decarbonization; Multicriteria Decision-Making; Sustainable Development

Nomenclature

Abbreviations

ANP	Analytic Network Process
$C-C$	Climate Criteria
$C-G$	Gender Criteria
$DANP$	DEMATEL - ANP
E	Energy actions
F	Food actions
G	Governance actions
$MCDM$	Multi Criteria Decision Making
M	Mobility actions
U	Urban planning actions

Symbols

A	Direct-relation matrix
a_{ij}	Values of the direct-relationships matrix
D	Sum of the columns of the Total-relation matrix
I	Identity matrix
k	Normalisation factor
R	Sum of the rows of the total-relation matrix
T	Total-relation matrix
t_{ij}	Values of the total-relationships matrix
X	Normalised direct-relation matrix
w_{ij}	Values of the weighted matrix

4.1 Introduction

Global warming is becoming evident as a problem that must be addressed. Evidence suggests that addressing global warming is crucial and needs to be approached both on a larger scale (global or national) and at the local level [1]. Cities are undergoing a significant effort toward decarbonisation. Cities concentrate over 75 % of the population in Europe [2], two-thirds of global energy consumption worldwide [3], and about 75% of CO_2 energy-related emissions [4].

Therefore, actions to mitigate their footprint are essential to achieve the objectives of the Paris Agreement. At the same time, cities present features such as heat islands and lower soil absorption capacities [5], which are highly dependent on background climate and urban fabric properties. Food and material dependency have regional sustainability implications that must be considered in urban planning, and policy-making [6]. These problems will require increasing actions to adapt cities, enhance their resilience to climate change and avoid increasing unequal impacts on them. Additionally, urban women often face significant disadvantages compared to men, such as limited access to decent work, constrained asset ownership, restricted mobility, safety concerns, and underrepresentation in urban governance [7]. Addressing these gender disparities is crucial for equitable urban development.

The European Mission "100 Climate-neutral and Smart Cities by 2030" encourages these efforts at the EU level [8]. The Mission involves local authorities, citizens, businesses, investors, and regional and national authorities to deliver 100 climate-neutral and smart cities by 2030 and ensure that these cities act as experimentation and innovation hubs so that all European cities follow suit by 2050. The Mission is the European Commission's most important program for achieving decarbonisation at the urban level. Accordingly, governments and institutions promote various policies and programmes to achieve this goal. However, the mainstream approach and technocratic tradition may favour detachment from social aspects over sustainability, resulting in the persistence of social inequalities, energy injustices, and citizens' passive participation [9]. Cities should prioritise actions that aim to reduce their carbon footprint while contributing to a more inclusive, democratic and just scenario through urban decarbonisation [10].

Gender disparity is one of the key challenges when tackling injustices in urban areas [7]. Gender studies have highlighted how policies and actions not drafted and planned with a gender perspective tend to produce a gender bias [11]. Climate policies are not exempt from this bias [12], and several studies highlight how some actions towards decarbonisation create gender inequalities [13–15]. The European Green New Deal and the European Gender Equality Strategy are clear messages that both environmental protection and gender equality are priorities for the European Commission. Nevertheless, these strategies lack coordination, and in most cases, the objectives are not addressed together. Policies must address the complexities of gender roles and identities and the root causes of inequality in the climate change context if they aim to be effective and redistributive [16, 17].

Although there is literature on the impact of climate policies on gender, it is focused on providing a knowledge base on how climate policies impact gender and vice versa [18, 19]. Others have studied how a specific type of sustainable urban measures affect the gender gap, e.g. Vajjarapu et al. [20] studied how sustainable urban transport measures affect differently depending on income and gender, while Gonda [21] explored a feminist political ecology framework to show how policymakers struggle to implement the complex climate and gender relationships in their policy formulation. Indeed, returning to the European framework, the Mission "100 Climate-Neutral and Smart Cities by 2030" mentions inclusiveness and the gender perspective. However, it lacks guidelines and specific targets that include a gender perspective in transforming cities to climate-neutral. As far as current research indicates, the literature has not yet made a concerted effort to rank and quantify the impacts of urban policies on both gender and climate aspects. Particularly, how do urban decarbonisation actions contribute to close the existing gender gap in cities?

This research proposes prioritising urban actions regarding climate and gender criteria to close this gap. The contribution of this research is threefold. First, it aims to map the urban decarbonisation actions that generate non-negative consequences to the gender perspective and to characterise the main climate and gender criteria affected by urban policies. Second, the research aims to quantify the influences between them and their expected positive impact on both gender and climate criteria. Third, due to the silos approach in developing urban policies [22], the research aims to understand the existing biases in evaluating these actions regarding the professional experts' background and their impact on gender or climate criteria. In sum, the aim is to improve the limited comprehension of the issue among decision-makers and practitioners.

Given the extensive range of gender and climate criteria, this study suggests the utilization of a Multicriteria Decision-Making Method (MCDM) as an approach to address this challenge. The evaluation of urban policies establishes connections with a comprehensive set of climate and gender criteria, centring on medium-sized cities in southern Europe. Although urban climate policies have a cross-cutting influence that impacts numerous domains, concentrated efforts are noticeable in areas with heightened emissions and in governance aspects.

The analysis focuses on five key policy dimensions: energy, food, governance, mobility, and urban planning. Within each of these dimensions, initiatives of policies that yield positive or neutral results from a gender perspective are outlined, and their alignment with four distinct climate and gender criteria is assessed. To facilitate this assessment, the study employs the DEMATEL-ANP (DANP) technique, used to ascertain the contributions of policies toward climate action and gender equality. Expert input from various domains is solicited to engage with the DANP model, enabling comparisons and relationships between criteria and actions.

The findings, according to the consulted experts, show which policies have the greatest potential to reduce cities' carbon footprints while also increasing gender equality. The results also show that if policymakers aim to promote equitable decarbonisation of cities, social factors should be broadly considered. Prioritisation of policies changes when only gender criteria or climate criteria are considered. Furthermore, policies are prioritised differently depending on the expertise field.

This study aims to provide both theoretical and methodological contributions to the field of urban, climate, and gender policies. From a theoretical point of view, the results (prioritisation of criteria and actions) serve as a learning tool for the research field since they complement previous studies and can provide new perspectives for city council managers on urban public policies over time. From the methodological point of view, the contribution is twofold. Firstly, the combination of methodologies, DEMATEL and ANP, is novel in the context of climate and gender policies. Secondly, the description of the process followed allows it to be replicated in other contexts or with different groups of experts.

4.2 Bridging complexities between gender and climate in urban decarbonisation policies

This section presents an overview of the current state of the art on the interaction between climate policies and gender implications at an urban scale. This issue's complexity and multidisciplinary nature lead us to assess it with MCDM techniques. The second part of the section describes and outlines similar approaches to these interactions.

4.2.1 Gender perspective approach in urban decarbonisation policies

Urban climate policies are cross-cutting issues and strategic for decarbonisation because they account for most Greenhouse gas emissions. According to the European Environmental Agency [23], the main emission sectors worldwide are energy, industry, transport, residential/commercial, agriculture and waste. Furthermore, the Intergovernmental Panel on Climate Change "Climate Change 2022: Impacts, Adaptation and Vulnerability" report [24] cites energy, urban and other settlements, transport, buildings, industry, agriculture and other land use as sectors where mitigation should be addressed. According to the Intergovernmental Panel on Climate Change "Climate Change 2014: Impacts, Adaptation, and Vulnerability" report [25], the key adapting sectors at the urban scale are energy, transport, food, housing, and urban planning. This report also outlines the role of government, planning, and management in putting the urban environment in place.

The transition to more resilient cities should include justice, not just the avoidance of unjust outcomes, but also the consideration of resilience engineering as a means of promoting urban justice [26]. It is necessary to go beyond plans and objectives and focus on actions [27]. Although climate change and its related policies are likely to have profound consequences for gender relations [28], policies focus on the economic and technical aspects, with justice issues, such as gender inequalities, playing a marginal role [29]. Cities have been planned and designed to reflect traditional gender roles and the gender labour division. Consequently, cities work better for men than for women [30]. If urban decarbonisation policies do not acknowledge and reflect these inequalities in their designs, they will perpetuate them. Some of these inequalities relate to time access due to differences in care tasks [31]; access to spaces of power, decision and participation [32]; economic and income disparities [33]; and urban mobility, access and usage of the public space [34].

For instance, when the gender representation of sectors is examined, it is noticeable that the sectors with the most significant carbon impact also have a low representation of women [35]. Energy, transport, housing and agriculture are also analysed as crucial sectors in other reports on climate change policies and gender, where women’s inclusion in decision-making and other aspects of governance is also highlighted as decisive [36–38]. These previous studies emphasise the importance of including a gender perspective in climate change action [36]. However, the role that the gender perspective plays in climate action is limited [29, 35]. These studies do not quantify the effects of urban policies simultaneously in gender and climate spheres or assess the bias produced due to the expertise field of the decision-makers.

The gender implications of urban policies designed to mitigate and adapt cities to climate change arise at different scales and viewpoints. Climate urban policy actions differ regarding their sectorial approach. Urban administration departments and policy actions tend not to be connected and conceive themselves as separated silos [22], but gender and climate implications have common approaches and interdependent objectives.

4.2.2 Multi-Criteria decision methods

This multidisciplinary combination of quantitative and qualitative objectives makes MDCD techniques appropriate for assessing their interactions. In particular, this study uses a combination of DEMATEL and ANP (DANP), two widely used MDCM techniques. Several studies employ these techniques to assess climate, gender, and urban issues in a complex context that combines qualitative and quantitative information. In climate terms, these methods are applied to the study of barriers to renewable energy sources at a national scale [39], the selection of technologies for rural electrification [40], and the barriers to transport decarbonisation at an urban scale [41]. Its application in gender studies is focused on understanding aspects related to customer behaviour [42, 43] but also in more strategic studies associated with policy strategies such as [44].

Regarding the analysis at an urban level, recent studies have tackled the selection of urban-related issues with MCDM approaches. Addae et al. apply DEMATEL to analyse the barriers to Smart Energy City in Accra [45], and [46] explores the compelling factors that drive urban development projects for Tehran in Iran. Two studies dice into the prioritisation of development strategies for tourist development and the pedestrianisation of the streets of Cartagena de Indias in Colombia [47, 48]. Finally, [49] assesses the management of urban transport systems for Donostia-San Sebastian in Spain and audits the city's local government in its policy decision-making processes. Therefore, these studies show the usefulness of MCDM methods, particularly DEMATEL and ANP, to climate, gender, and urban issues. While some of these studies combine two of these approaches, none of them holistically combines the three of them nor uses the combination of DEMATEL and ANP for the approach.

DEMATEL is an MCDM technique used to analyse the relationships between different criteria or objectives. In this research, the criteria would be both gender and climate criteria, where DEMATEL evaluates the interdependence among them. A group of experts would be asked to evaluate the relationships between the different criteria using a structured questionnaire. The experts would rate the strength and direction of the relationships between the criteria, with higher numbers indicating a stronger relationship. Based on the responses from the experts, the DEMATEL method would be used to identify the most important criteria and to determine how they are interrelated. This information could then be used to evaluate the different policies or initiatives, considering the impact on gender equality and climate change criteria. This analysis could help inform decision-making by providing a better understanding of the potential trade-offs and synergies between different objectives, which is one of the main objectives of this paper.

The Analytic Network Process (ANP) is also an MCDM technique used to evaluate and compare options or alternatives based on multiple criteria. It is based on the idea that the criteria and options being considered are interrelated, and the relative importance of each criterion can change depending on the context. Thus, ANP is well-suited to complex decision-making situations where many criteria need to be considered and where the relative importance of each criterion can vary.

The combination of the two techniques allows both advantages to be exploited. The ANP allows a comprehensive analysis of the influences of all the elements that make up a network. The number of questions required by the ANP is very high, as it works with paired comparisons for all the triads of the network. Thus, DEMATEL will be used instead, which requires a much lower number of questions for the experts as it works with direct influences rather than through comparisons, consequently saving time. In addition, DEMATEL allows a cause-effect analysis of the different network elements involved, which would not be possible if only the ANP was applied [50–52]. Studies have used the combination of these two techniques on many previous occasions with success. In the field of climate change, the methodology has been used recently by [53] analysing the influence of some key factors when looking for urban carbon neutrality in a city of China, [54] analysing the factors to prioritise and select renewable energy resources. However, to the best of the authors' knowledge, this methodology has never been used before, either in gender equality research or in the combined analysis of climate and gender aspects.

4.3 Study design and method

The methodology used to approach this research is organised in two stages. The first stage, *Preparation of the prioritisation model*, is a stage that could be replicated in any study whose objective is to analyse the impact of policy actions in which there are several influencing criteria. This step is carried out by the facilitators of the prioritisation process, in this case, the authors involved in this research and does not require the collaboration of the expert group. The second stage, *Resolution of the prioritisation model*, requires the participation of experts and must, therefore, be adapted according to the context of the case study. It involves answering lengthy questionnaires that need a little preparation and description beforehand. Access to information from the experts has to be adapted to the characteristics of the experts.

The second stage uses an integrated MCDM approach based on a combination of DEMATEL and ANP (DANP) to determine the impact of urban policy actions simultaneously on urban decarbonisation and gender gap closure. This is accomplished through an evaluation of different gender criteria for the two goals of urban decarbonisation and gender gap closure. The selected policy actions belong to five clusters (energy, food, governance, mobility, and urban planning). All the selected actions have at least a theoretical non-negative outcome regarding climate and gender objectives.

Multi-criteria analysis is used to evaluate the actions and the criteria, enabling ranking of the actions concerning the two objectives. Figure 4.3.1 presents the different steps of the methodology that guided this study. Each major step is described in detail in the following subsections.

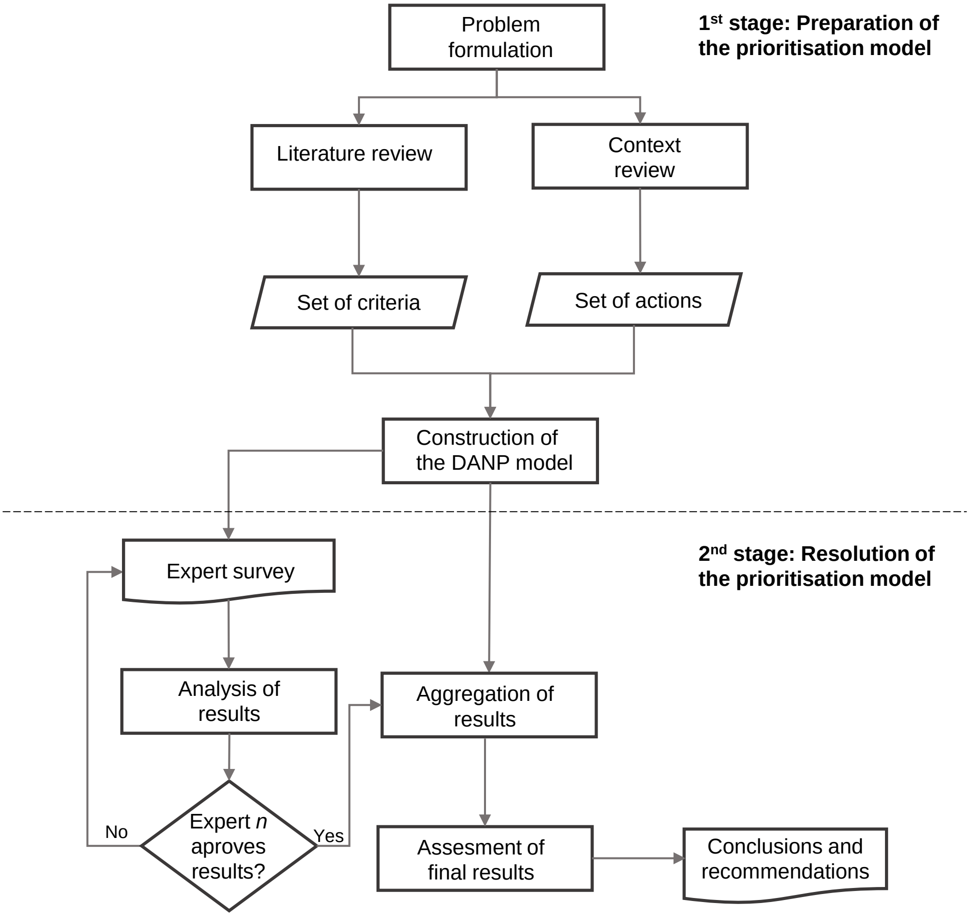

Figure 4.3.1: Summary of the followed methodology.

4.3.1 Definition of the model

The ranking model is based on a network of criteria and actions that influence each other. The criteria and actions are derived from a literature and context review that experts validate. Both climate and gender criteria are selected to represent the diversity of elements in consideration to achieve both goals. The policy actions include mature measures commonly implemented by city planners and promoted by urban stakeholders. Socio-technical sectors and specific governance policies cluster actions. To ensure the model's traceability, maintaining adherence to a maximum of four criteria and actions within each cluster is upheld. This approach captures the diversity of policy actions and criteria without making the model intractable for expert consultation nor losing detailed comparison between representative elements of the model.

4.3.2 Consultation with experts

A panel of experts is selected to assess the criteria. Experts from different socio-technical systems considered policy actions in the model. Therefore, experts have professional backgrounds in energy, food, governance, mobility, and urban planning. In this type of MCDM technique, due to the semi-quantitative and expert nature of the information, the quality of experts is crucial compared to the number of them [55]. Experts should thoroughly understand their field's implications in the case study and a holistic view of urban transformation. Due to the interdependence between urban actions and climate and gender criteria, the experts have expertise in their fields and evaluated criteria but also understand the rest of the actions. Experts' backgrounds are diverse and formed by academics, urban public policy-makers, and private sector professionals.

A total of seventeen experts were consulted to answer the DANP questionnaire. The experts were selected based on their area of knowledge, i.e. their background expertise. For this purpose, experts from these five areas were selected: energy, food, governance, mobility and urbanism. The experts selected are people working in academia, Valencia City Council or private companies with a professional link to urban policies. An attempt has also been made to ensure gender parity in each group. While the specific number of experts required for a decision-making process can vary depending on its complexity and scope, working with 17 experts can indeed be sufficient when they are carefully selected to represent the problem's interests and are committed to collaborative efforts. The advantages of a smaller, focused team include enhanced expertise, efficiency, collaboration, and adaptability, all of which contribute to the likelihood of a successful study. It is also important to ensure that there is a commitment from the experts to the proposed task, as it requires time and some effort. The experts should be closely attentive to how they respond. In Table 4.3.1, the list of experts is shown, along with their areas of expertise and affiliation.

Table 4.3.1: List of experts.

Id.	Expertise	Sector
Ex1	Energy	Academia
Ex2	Energy	Academia
Ex3	Energy	Academia
Ex4	Energy	Academia
Ex5	Energy	Public sector
Ex6	Food	NGO
Ex7	Food	NGO
Ex8	Governance	Academia
Ex9	Governance	Academia
Ex10	Governance	Academia
Ex11	Governance	Academia
Ex12	Governance	Academia
Ex13	Mobility	Academia
Ex14	Mobility	Private sector
Ex15	Urbanism	Private sector
Ex16	Urbanism	Private sector
Ex17	Urbanism	Public sector

When arranging the groups of experts, it must be ensured that these groups present a sufficient degree of compatibility based on the Garuti and Kendal indexes. Experts inside a group are compatible with at least another expert, considering either a Garuti index above 0.85 [56] or a Kendall p value above 0.6 [57].

4.3.3 Weighting of the criteria and actions

Once the model is drawn and validated by the experts, the DANP method is applied in five steps.

Step 1: Generation of the direct-relation matrix A. First, measuring the relationship between criteria requires that the comparison scale is designed in a 0-4 scale:

- 0 (no influence)
- 1 (low influence)
- 2 (medium influence)

- 3 (high influence)
- 4 (very high influence)

Experts make pairwise comparisons of the influences between criteria and between criteria and actions. Then, the initial data is obtained as the direct-relation matrix. The A matrix is a nxn matrix in which a_{ij} denotes the degree to which the criterion i affects the criterion j.

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:

$$X = k \times A \tag{4.3.1}$$

$$k = \frac{1}{\max\limits_{1 \le i \le N} \sum_{j=1}^{n} a_{ij}} \tag{4.3.2}$$

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

Step 3: Attaining the total-relation matrix: T can be obtained by using Equation 4.3.3, in which the I is denoted as the identity matrix

$$T = X(I - X)^{-1} \tag{4.3.3}$$

Once all the values of the matrix T have been obtained, the value of the individual influences that each of the criteria in the rows exerts on the other criteria of the network in the columns, i.e. the influences of the criteria on each other, is obtained. In this way, by setting influence thresholds, the most prominent relationships of the criteria network can be discovered.

Step 4: The parameters D and R for each criterion are obtained from the values of the matrix T using the Equations 4.3.4 and 4.3.5. The two values for each criterion allow us to obtain the causal diagram of the criteria.

$$D = \sum_{j=1}^{n} t_{ij}, i = 1, 2, ..., n \tag{4.3.4}$$

$$R = \sum_{i=1}^{n} t_{ij}, j = 1, 2, ..., n \tag{4.3.5}$$

The cause-effect diagram enables the analysis of the degree of prominence, indicated by the sum of D and R (horizontal axis), and the degree of cause or effect, indicated by the subtraction of D and R (vertical axis).

Step 5: Normalising each column of the T matrix (unweighted) by its sum, the weighted supermatrix is obtained.

$$w_{ij} = \frac{t_{ij}}{\sum_{i=1}^{n} t_{ij}} \tag{4.3.6}$$

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

Step 6: 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 criteria and action values are extracted from the vector of the limit supermatrix and normalised by the sum to obtain their final weights. In this way, the ranking can be obtained, which will allow for an understanding of the decision profile of the experts. 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.

4.3.4 Analysis of the results

The study results are presented with different granularity levels: expert, group, and aggregated. The results focus on both criteria and policy actions. Besides, two extra models are presented where either only climate criteria or only gender criteria are considered. When clustering the DANP results, the group limit supermatrix represents the aggregation of the group experts' matrices. The aggregation is performed with a geographic mean, as suggested in [58]. That is, the Food group results represent the geographical mean of all the individual results of the Food experts, while the mean results represent the combination of all experts' judgements. Since DANP is based on expert opinions, it is essential to recognise the potential for subjectivity inherent in expert judgements when interpreting the results. This potential source of error can be mitigated by involving sufficient experts with varied experience [55].

4.4 Model description

Figure 4.4.1 presents the ranking model characterised by a network of clusters of criteria and actions. The model is framed in the context of medium-sized European cities. Both the criteria and actions are derived from a literature review. The actions include measures to be implemented by city planners and all stakeholders involved at the city level or influencing it. A set of criteria is selected to represent achieving both goals, climate change mitigation and adaptation and closing the gender gap. Four criteria represent each goal.

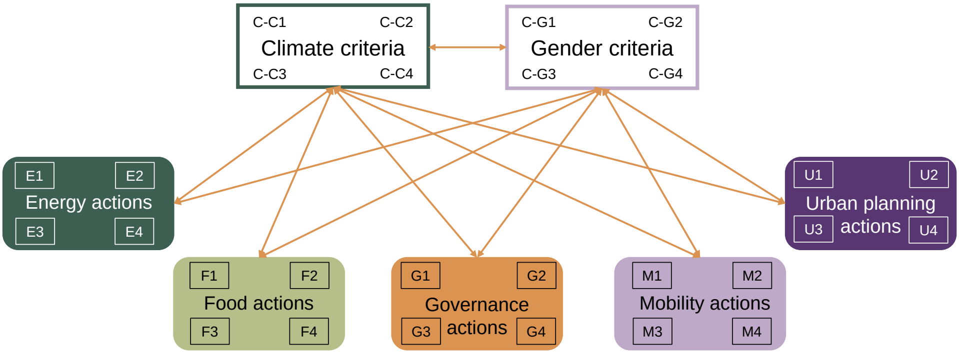

Figure 4.4.1: Overview of the studied model

Table 4.4.1 presents both climate and gender criteria. Climate criteria refer to reductions in emissions (C-C1), rationalisation of energy and raw material consumption (C-C2), increasing energy generation from renewable energy sources at the urban level (C-C3) and adapting cities to the impacts of climate change (C-C4). Regarding gender criteria, these refer to the visibility of care tasks (C-G1), the access of women to work and decision-making positions (C-G2), women's safety (C-G3), and the free and safe movement of women (C-G4).

Table 4.4.1: Set of climate and gender criteria.

Id.	**Climate criteria**	**Refs.**
CC1	Reduction of emissions associated with economic and social activity.	[59, 60]
CC2	Rationalisation and reduction of energy consumption and raw material consumption.	[61, 62]
CC3	Increasing energy generation from renewable sources.	[63, 64]
CC4	Improving urban resilience to the impacts of climate change.	[63, 65]
	Gender criteria	
CG1	Visibility, co-responsibility and improvement of conditions for the development of care tasks.	[66, 67]
CG2	Women's access to and improvement of conditions for fair work, participation and decision-making environments.	[68, 69]
CG3	Women's safety and reduction of violence against women and other vulnerable minorities.	[70–72]
CG4	Autonomy and economic independence and independence of women's movements for the development of a personal project.	[73, 74]

Following the criteria selection, Table 4.4.2 presents all the policy actions analysed, classified into five clusters: food, governance, mobility, energy, and urban planning. These actions are selected based on common policy intervention at urban scales. The policy actions vary from direct public intervention, such as Improving the public transport network (M1) or Increasing the diversity of uses in dense urban areas (U1) to economic incentives to achieve objectives, such as Promoting self-consumption (E1) or Ensuring energy efficiency in the residential stock (E2) or softer decision-making actions such as Promoting healthy public procurement with environmental and social criteria (F4) and Governance actions.

Table 4.4.2: Set of policy actions.

Id.	Energy	Refs.
E1	Promoting self-consumption: individual, collective and energy communities.	[75–77]
E2	Ensuring energy efficiency in the residential stock.	[78, 79]
E3	Direct aid for fuel poverty.	[80, 81]
E4	Energy education	[82, 83]
	Food	
F1	Promoting production and access to organic products	[53, 84]
F2	Reduce animal protein consumption	[85, 86]
F3	Promote sustainable consumption and markets	[87, 88]
F4	Promote healthy public procurement with environmental and social criteria	[84, 89]
	Governance	
G1	Ensuring the presence and participation of women in jobs and decision-making	[13, 90]
G2	Promote neighbourhood cooperative projects and community organisation.	[91, 92]
G3	Designing and implementing citizen engagement processes.	[93, 94]
G4	Analyse and evaluate measures and actions from a gender perspective.	[38, 95]
	Mobility	
M1	Improve the public transport network including inter-modality and metropolitan connection	[96, 97]
M2	Implementation of a dense network of pedestrian and cycle routes	[98, 99]
M3	Promote car-sharing platforms.	[100, 101]
M4	Promote EVs: Replacement and infrastructure	[102, 103]
	Urban planning	
U1	Increasing the diversity of uses in dense urban areas.	[104, 105]
U2	Re-naturalise urban open spaces and connect green infrastructure.	[106, 107]
U3	Ensuring access to decent housing.	[108, 109]
U4	Adapt housing to new standards of quality, diversity and accessibility.	[110, 111]

4.5 Results and discussion

This section presents the results of the study in four main parts. Initially, the role of each criterion in the model is delineated, along with an exploration of their mutual interactions. Subsequently, an analysis is conducted to ascertain the relative weight of various policy actions. Then, the results are divided considering the biases, first by the expert group and finally by comparing the complete, climate, and gender models.

4.5.1 Weight and interaction of the criteria

The DANP method prioritises the selected criteria and actions from the most to the least important for the decarbonisation of a city while closing the gender gap simultaneously, according to the participant experts.

The prioritisation of criteria for the aggregated group of experts is shown in Figure 4.5.1. Three climate criteria and one gender criteria stand out slightly: rationalisation and reduction of energy consumption and raw material consumption (C-C2), improving urban resilience to the impacts of climate change (C-C4), reduction of emissions associated with economic and social activity (C-C1), autonomy and economic independence of women's movements (C-G4), and fair work and participation and decision-making (C-G2). This result shows how experts prioritise climate criteria over gender criteria, focusing on criteria that mainly affect urban metabolism and its dependence on inputs and adaptation needs. Regarding gender criteria, the ones with more significant importance are the ones related to decision-making and the economic sphere of gender inequalities. According to the experts, the other gender criteria regarding co-responsibility and safety (C-G1 and C-G4) follow the outstanding group. Finally, a lower prioritisation is given to increasing energy generation from renewable resources (C-C3), which relates to the constrained nature of renewable energy generation in urban areas.

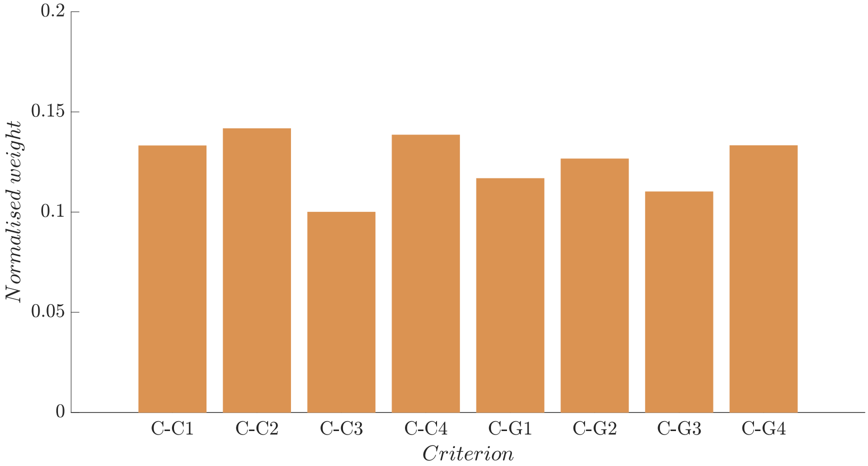

Figure 4.5.1: Aggregated weight of criteria

Regarding criteria influences, Table 4.5.1 presents the aggregated value of the influence of each criterion against each other. This is the total relationship matrix mentioned in Step 3 of the weighting procedure (Equation 4.3.3). The highest influences have been highlighted. Two thresholds have been calculated to indicate two different levels of influence [53]:

- Threshold 1. Moderate influence: mean (0.069)
- Threshold 2. High influence: mean plus standard deviation (0.090)

The results show that within the gender cluster, criteria are highly influenced by each other, and climate criteria are also highly influenced by each other. Still, climate criteria do not highly influence gender criteria or gender criteria climate criteria. Regarding the influence between the two clusters and when considering moderate influences, the gender criteria influence the climate criteria, while the climate criteria have very little influence on gender criteria. A Cause-Effect diagram is presented in Figure 4.5.2 (see Step 4 in section 4.3.3) in which the X-axis shows the degree of importance of each factor. In contrast, the Y-axis shows each factor's degree of cause (positive values) or effect (negative values). As can be seen in this diagram, criteria are classified into four quadrants [53]. It can be observed that

Table 4.5.1: Total Relationship Matrix among criteria. Grey values are below the relationship average, black values are values above the average, and bold values are values above the average plus one standard deviation.

	C-C1	C-C2	C-C3	C-C4	C-G1	C-G2	C-G3	C-G4
C-C1	0.0628	**0.0997**	0.0726	**0.0950**	0.0497	0.0504	0.0476	0.0590
C-C2	**0.1145**	0.0641	0.0758	**0.0983**	0.0596	0.0610	0.0527	0.0753
C-C3	**0.0987**	0.0827	0.0318	0.0805	0.0391	0.0439	0.0380	0.0567
C-C4	**0.0956**	**0.0972**	0.0717	0.0592	0.0649	0.0653	0.0650	0.0778
C-G1	0.0704	0.0732	0.0415	0.0698	0.0421	0.0864	0.0790	**0.0972**
C-G2	0.0799	0.0795	0.0543	0.0789	**0.0915**	0.0467	**0.0928**	**0.1027**
C-G3	0.0549	0.0562	0.0395	0.0629	0.0793	0.0812	0.0409	**0.0969**
C-G4	0.0761	0.0757	0.0529	0.0771	**0.0935**	**0.1016**	**0.0926**	0.0551

the four gender criteria and one of the climate criteria are causal factors. They get positive D+R and have a certain effect on all other indicators. The only criterion in the II quadrant is C-G4 Autonomy and economic independence and independence of women's movements for developing a personal project, which can be regarded as a critical factor and should be considered when designing actions.

From the interaction of the criteria, it is concluded that despite the greater importance of the climate criteria for decarbonising cities, these criteria do not influence the gender criteria. Therefore, not considering gender criteria may result in a transition without a fair gender perspective. This finding backs up what the literature says about the risk of technocratic visions of energy politics [29].

In contrast, the gender criteria do influence the climate criteria. Incorporating a gender perspective into policies for major sustainability transition processes can engage and reinforce these processes, as authors such as Braunger et al. [90] pointed out.

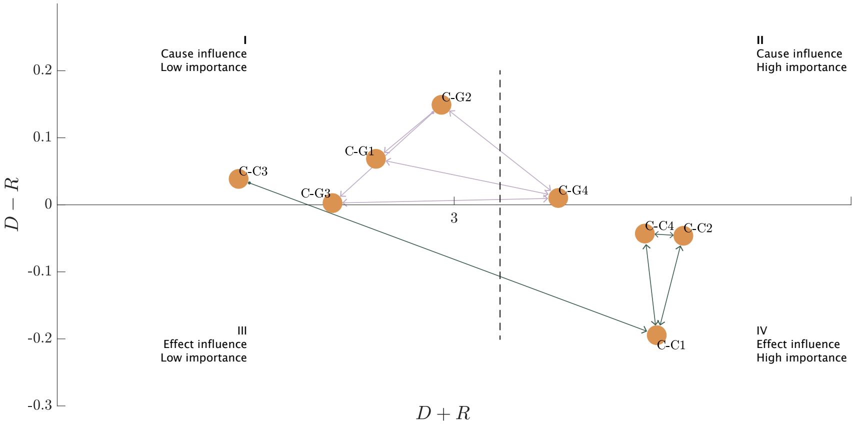

Figure 4.5.2: Causal diagram

4.5.2 Weight and dispersion of the actions

Figure 4.5.3 shows the final average priority of each action for the whole group of experts. According to them, the actions that better contribute to the two goals are improving the public transport network (M1), ensuring the presence and participation of women in jobs, decision-making and project management (G1), analysing and evaluating measures and actions from a gender perspective (G4), promoting neighbourhood cooperative projects and community organisation (G2), and implementing of a dense network of pedestrian and cycle routes (M2). In contrast, promoting electric vehicles (M4) is the lowest-scoring action.

Governance actions are of great importance and belong in the most important cluster. This result is interesting because governance complements many other actions due to its more organisational and less capital-intensive role. Thus, governance actions could complement more capital-intensive actions in the built environment, such as mobility, urban, and energy. The first two mobility actions are of great importance due to the high impact of mobility in cities and the considerable emission reduction potential of these promoting public transport and cycling or foot trips. Concerning mobility actions, U1 is one of the two most valued urban plan actions due to the significant correlation between reducing mobility needs and having a diversity of uses and densely populated areas. Meanwhile, U4 relates to the residential energy demand in cities, which correlates with E1 and the promotion of renewable generation in cities.

The first group of the presented capital-intensive actions respond to the need to reduce transport emissions, while the second one responds to and resolves the energy needs in buildings. These two elements represent the primary sources of city emissions due to a common absence of industrial facilities in urban areas. Besides, these actions relate to areas where urban policies have competencies to mitigate and adapt to climate change. The rest of the actions with larger scores relate to actions with no infrastructural changes, such as governance actions and E4 energy culture, which have a significant impact at a climate level but especially on a gender level.

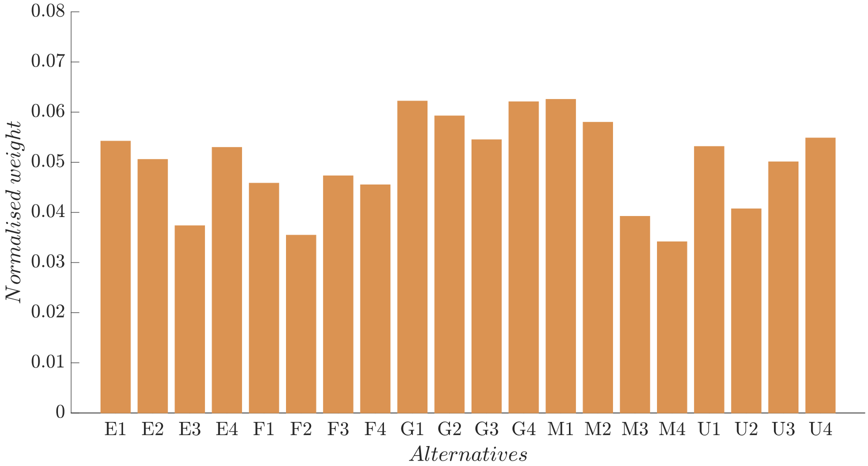

Figure 4.5.3: Aggregated weight of actions

Figure 4.5.4 shows the dispersion of the evaluation of policy actions according to the whole group of experts. Of particular relevance are those actions without layers that show significant discrepancies among experts. It is important to note that while Governance actions are prominent, they do not present any large discrepancy among the seventeen experts.

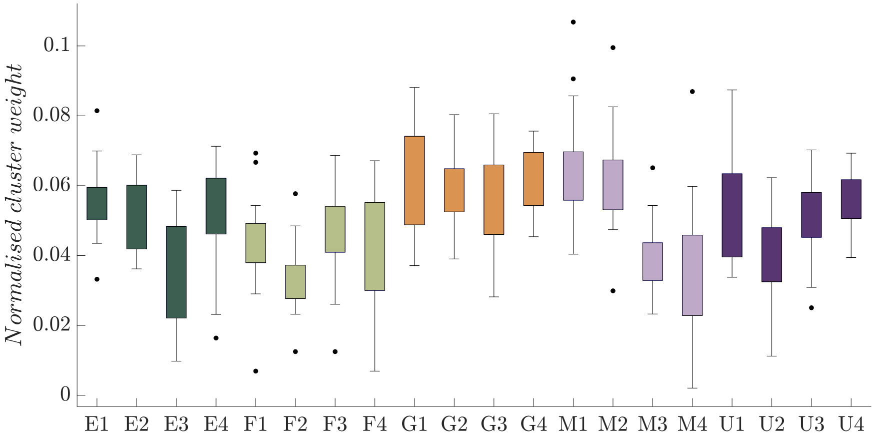

Figure 4.5.4: Dispersion of the value for each action

4.5.3 Bias by expert type

The results are analysed according to the experts' field of knowledge, as shown in Figures 4.5.5 and 4.5.6. Figure 4.5.5 highlights how experts prioritise the criteria with some differences depending on their expertise field. However, rationalisation and reduction of energy consumption and raw material consumption (C-C2) is among the two main criteria for four of the five groups of experts. Nevertheless, energy experts attach the greatest importance to reducing emissions associated with economic and social activity (C-C1). In contrast, urban and governance experts emphasise improving urban resilience to the impacts of climate change (C-C4), and mobility experts prioritise autonomy, economic independence, and independence of women's movements (C-G4). Food experts maintain a similar level of prioritisation across all criteria.

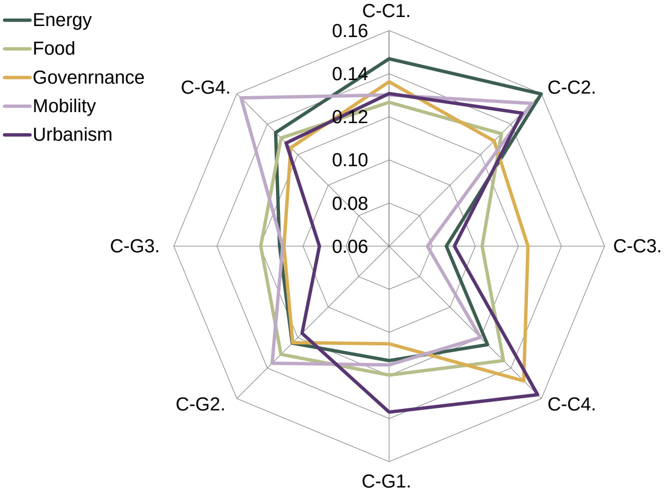

Figure 4.5.5: Analysis of the criteria considering the bias by expert's group.

Figure 4.5.6 shows how the priority of actions varies depending on the respondents' expertise field, although governance importance is extended among all groups. Urban planning and mobility experts tend to allocate higher importance to mobility and urban planning actions (M1, M2 and U1), while governance experts prioritise the governance actions. Energy experts give the highest value to most energy actions (E2, E1 and E4). Food experts are the only experts giving a high priority to a food action (F4). These results show expert decision-making is biased toward their field, reinforcing the need for multidisciplinary decision-making teams to have complementary perspectives.

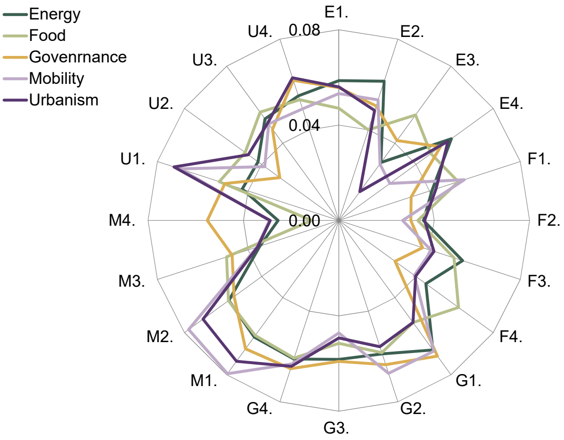

Figure 4.5.6: Analysis of the actions considering the bias by expert's group.

4.5.4 Bias by criteria type

Finally, Figure 4.5.7 presents the bias between criteria, considering the results when the model only considers climate or gender criteria, showing a variation between action priorities. In this sense, this study aims to deliver in this analysis how the prioritisation of actions would be if only one group of criteria is considered. One criteria group is eliminated from the general DANP model to analyse this. Hence, the sequences studied only refer to the criteria in the model on the actions or alternatives for analysis.

For the climate model, when only climate criteria are analysed, the main actions are promoting self-consumption in individual, collective and energy communities (E1), ensuring energy efficiency in the residential stock (E2), energy education (E4) and improving the public transport network (M1). The importance of all energy cluster actions is increased compared to the general model, except for the case of action E3. Direct Aid for Fuel Poverty is a measure with more impact on social emergency than decarbonisation, as it involves economic aid to vulnerable socioeconomic groups. At the same time, for the gender model, consequently, this action rises. Furthermore, it is observable that governance actions experience a decrease in priority, whereas actions within the remaining clusters garner heightened significance.

For the gender model, when only gender criteria are analysed, the main action differences belong to analysing and evaluating measures and actions from a gender perspective (G4), ensuring the presence and participation of women in jobs and decision-making (G1), promoting neighbourhood cooperative projects and community organisation (G2) and ensuring access to decent housing (U3). In this model, governance actions become significantly more relevant than the general model and less relevant for the climate model, correlating to the importance of governance actions to reduce gender biases.

Some actions of urban planning and mobility clusters (M1, M2, U1, and U4) follow a consistent trend independently of the model, i.e., type of criteria. The reason to focus on these actions is that, in addition to consistency, regardless of the criteria followed, they have high importance in the overall result (Figure 4.5.3). Nevertheless, most actions are affected by the type of criteria applied. That is, some actions increase, and others decrease in importance when analysing each model separately.

When comparing the climate model with the complete model, some actions significantly reduce their importance by including gender criteria. Among these actions are E1, E2 and E4, the most important actions according to the climate model. In the complete model, adding gender criteria, actions with more social elements gain importance. This can be seen in the difference between the climate model and the complete model in Figure 4.5.7, where the complete model shows a greater emphasis on governance action, ensuring access to decent housing (U3) and adapting housing to new standards of quality, diversity and accessibility (U4) and direct aid for fuel poverty (E3). Therefore, it can be concluded that there is a gender bias in these actions, and thus, the energy transition needs specific gender criteria to be inclusive.

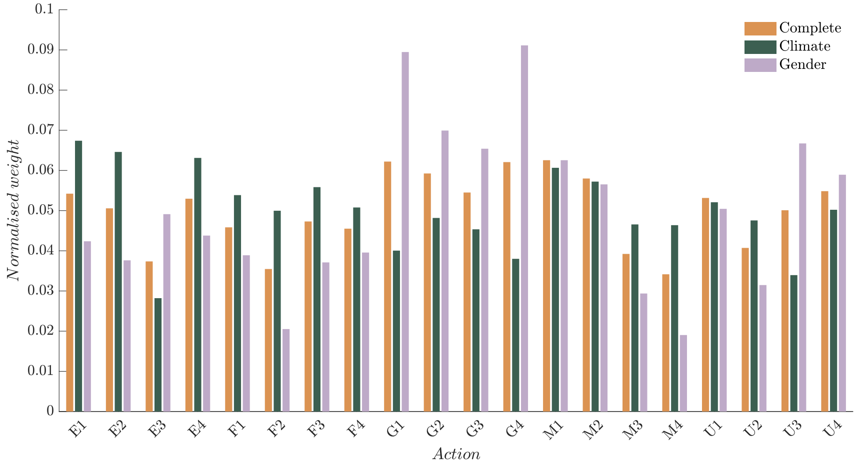

Figure 4.5.7: Aggregated weight of actions considering only Climate or Gender criteria

In sum, the main actions to be implemented change whether gender criteria are included. If gender criteria are not included (climate model), there is a bias towards actions with a more technical component. When gender criteria are included (full model), such actions of a purely technical nature lose importance to actions with more social elements.

Furthermore, it is essential to note that according to the criteria analysis (Section 4.5.1), the gender criteria influence the climate criteria. Considering gender criteria will also contribute to and reinforce climate objectives. However, the climate criteria do not influence the gender criteria, so they would not contribute to both objectives. Moreover, the actions that stand out considering gender criteria are governance actions, which can improve gender equality while reinforcing actions to be bolder in climate terms. Without gender criteria, actions with a technical component are favoured. If policymakers aim to promote just decarbonisation of cities, the inclusion of a gender perspective in general and particularly at governance levels should be broadly considered.

In the absence of a gender perspective in formulating urban decarbonization policies, there is a risk of perpetuating existing gender inequalities. The criteria analysis indicates that incorporating gender criteria plays a pivotal role in narrowing the gender gap, although it may simultaneously impact the decarbonization process, as suggested by the analysis. Conversely, when policymakers incorporate gender criteria into developing city climate policies, they can serve as catalysts for addressing urban inequalities. However, it's important to note that including gender criteria alone is insufficient to eliminate bias. To ensure unbiased and effective decision-making, it is imperative to involve multidisciplinary teams in the policy formulation process.

4.6 Conclusions

This study conducts a Multicriteria Decision-Making Method to assess urban policies and relate them to climate and gender criteria. Urban decarbonisation policies with non-negative gender outcomes are described, and their impacts are compared using climate and gender criteria. The DANP technique is used to determine how policies contribute to climate action and gender equality. Experts in the various fields involved in urban decarbonisation respond to the DANP model by comparing and relating criteria and actions.

First, the criteria for the two goals are established after a literature review. Then, actions with a non-negative outcome from a gender perspective are proposed in five critical areas for urban policies. Seventeen experts from the five action clusters responded to the DANP model by comparing and relating criteria and actions. Then, the results are analysed from three perspectives.

The first is considering the complete model that includes all the experts and the criteria of both groups. Governance actions are crucial, which is an interesting result given that governance complements many other actions due to its more organisational and less capital-intensive role. As a result, governance actions may be combined with outstanding mobility actions. Due to the significant impact of mobility within urban areas and the substantial potential for emission reduction associated with these two actions, the initial two mobility measures also attain a heightened level of importance.

The second one considers the field of expertise of the respondents. Experts prioritise the criteria differently depending on their field of expertise. However, rationalisation and reduction of energy consumption and raw material consumption are among the two main criteria for four of the five groups of experts. The priority of actions varies depending on the respondents' expertise field, although governance importance is extended among all groups. From these results, it is concluded that expert decisions are biased toward their field of knowledge. However, mobility experts highlight autonomy and economic independence and independence of women's movements for developing a personal project as the most relevant criterion. Regarding the results obtained, this criterion is the most influential and important criterion in the model and must be considered a key factor in designing policy actions.

The third one analyses the groups of criteria separately to observe how actions are prioritised according to each of the criteria groups: climate and gender. Gender criteria prioritise efforts with more significant social importance above technical elements. When gender criteria are included (full model), such actions of a purely technical nature lose importance to actions with more social elements. Furthermore, the gender criteria impact the climate criteria, according to the criteria analysis. Both results show that actions with significant social efforts will ensure a just transition as they would also catalyze and achieve the climate objectives needed.

To summarize, the results indicate that the inclusion of gender criteria affects the prioritization of actions. Without gender criteria, actions with a technical component are favoured. However, with gender criteria, actions involving social elements become more important. Additionally, gender criteria impact climate objectives, but not vice versa. The relationship between gender and climate criteria in policy actions is complex and context-dependent. While gender considerations can inform and enhance climate policies, climate change itself can also have differential impacts on different genders and necessitate specific gender-sensitive responses. To address these interrelated issues effectively, comprehensive policies should consider the bidirectional relationship between gender and climate criteria, ensuring that both are integrated into decision-making processes and strategies for a more sustainable and equitable future. If no gender perspective is used in formulating urban decarbonisation policies, these can lead to the reproduction of the existing gender inequalities. In contrast, if policymakers formulate climate policies in cities with gender criteria, these can become a catalyser to overcome these urban inequalities.

The prioritisation of urban policy actions changes depending on the goal of the focus. The ranking is different for the same actions depending on whether the purpose is only climatic or also closing the gender gap. Policymakers should take a gender perspective into account to achieve a just decarbonisation of cities. If both targets are set together, a better balance is established in the type of actions contributing to achieving just decarbonisation and creating a positive reinforcement loop between gender and climate criteria. Integrating gender criteria into urban decarbonization policies is not just about addressing gender disparities but also about creating more resilient, sustainable, and inclusive cities. This study sets a precedent for including gender criteria in urban policies to decarbonise cities. The study aims to facilitate the inclusion of gender perspective in the 100 Climate-Neutral and Smart Cities by 2030 Mission. The inclusion of gender criteria contributes to closing the gender gap while having a widening impact on decarbonisation, as the criteria analysis suggests. Nevertheless, including gender criteria is insufficient to avoid bias, and multidisciplinary teams must participate in decision-making. The process of analysis and synthesis can yield valuable insights and principles that guide the development of gender-sensitive climate policies in cities and interventions on a broader scale. While each context has its unique challenges and opportunities, local lessons can draw lessons that can inform and inspire more inclusive and effective climate policies in cities worldwide.

CRediT authorship contribution statement

Isabel Aparisi-Cerdá: Writing - original draft, Methodology, Visualisation, Data Curation. David Ribó-Pérez: Conceptualization, Methodology, Software, Data Curation, Visualisation, Writing - original draft, Writing - review & editing. J. Gomar-Pascual: Conceptualization, Methodology, Writing - review & editing. J. Pineda-Soler: Conceptualization, Methodology, Writing - review & editing. R. Poveda-Bautista: Conceptualization, Writing - review & editing, Supervision. Mónica García-Melón: Methodology, Supervision, Writing - review & editing.

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Data availability

Data used in this paper can be found in this link.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to avoid grammatical and spelling errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Chapter 5

Panel or check? Assessing the benefits of integrating households in energy poverty into energy communities

Panel or check? Assessing the benefits of integrating households in energy poverty into energy communities

[5] *Isabel Aparisi-Cerdá, Álvaro Manso-Burgos, David Ribó-Pérez, Nelson Sommerfeldt, Tomás Gómez-Navarro. "Panel or check? Assessing the benefits of integrating households in energy poverty into energy communities." Sustainable Energy Technologies and Assessments, vol. 71, pp. 103970-103982, 2024*

Abstract

This research raises the possibility for households in energy poverty to participate in shared photovoltaic systems in renewable energy communities (REC) to reduce their energy costs, with investment costs covered by public institutions. It begins by evaluating the current solution for vulnerable households, which relies on public subsidies to lower energy costs without addressing root causes or improving environmental impacts. The study compares traditional subsidies with REC participation for vulnerable households. By simulating a REC composed of such households, the results indicate that REC participation is more cost-effective for public institutions than energy subsidies. At the economically optimal size of 31 kWp, the cost of subsidies decreases by 58,000 €, a 50% reduction, with household savings increasing by 6%. At 58 kWp, the need for additional support checks is eliminated, increasing household savings by 65% but with a lower NPV of 22,500 €. The largest viable system, 75 kWp, increases average household savings by 82%. This approach also leads to a net reduction in GHG emissions, engaging previously excluded households in the energy transition.

Keywords

Energy poverty; Just energy transition; Self-consumption; Renewable energy communities; Energy checks

Nomenclature

Acronyms

EU	European Union
NPV	Net Present Value
PV	Photovoltaic
REC	Renewable Energy Communities
RES	Renewable Energy Sources

Indices

b_0 & b_f	Beginning and end of the billing period
j	Load curve index
n	Year of operation index [yr]
s	Simulation scenarios index
t	Time index [h]

Parameters

C^G	Annual cost of electricity purchased from the grid [€ /yr]
C^{POW}	Annual cost of power term of electricity of the grid [€ /yr]
d	Market discount rate
EC	Bill reduction covered by the electricity check [%]
OM	Operation and maintenance annual expenses [€ /yr]
$P^D_{j,t}$	Power demand by consumer j at moment t [kW]
P^{PV}_{nom}	Nominal power of the PV system [kW]
POW_j	Contracted power in the load j [kW]
π^{POW}	Price of contracted power [€ /kW]

Sets

J	Set of all points of consumption
N	Set of years of operations
S	Set of all simulation scenarios
T	Set of all time periods

Subscripts

0	Original situation
REC	After REC implementation

Variables

β	Allocation coefficient
C^{PUR}_t	Cost of electricity purchased from the grid at moment t [€]
C^{SELL}_t	Cost of electricity sold to the grid at moment t [€]
C^V_t	Cost of the variable term of electricity from the grid at the moment t [€]
CF_t	PV capacity factor at moment t
INV_n	Investment at year n [€]
$P^A_{j,t}$	Power allocated to consumer j at moment t [kW]
$P^{GIFT}_{j,t}$	Power injected into the network without benefit by consumer j at moment t [kW]
$P^{PUR}_{j,t}$	Power purchased from grid by consumer j at moment t [kW]
P^{PV}_t	Power generated by the PV system at moment t [kW]
$P^{SC}_{j,t}$	Power consumed by consumer j directly from the PV system at moment t [kW]
P^{SELL}_t	Power sold to the grid at moment t [kW]
π^{PUR}_t	Price of purchased electricity at moment t [€ /kWh]
π^{SELL}_t	Price of sold electricity at moment t [€ /kWh]

Metrics

NPV^{INV}_n	NPV of investment at year n [€]
NPV^{REC}_n	NPV of REC at year n [€]
NPV^{OM}_n	NPV of OM at year n [€]
NPV^{SAV}_n	NPV of savings at year n [€]
SAV	Annual billing savings generated by the REC [€]

5.1 Introduction

In recent years, the European Union (EU) has witnessed a concerning rise in energy poverty, bringing to light a significant societal challenge. This issue, impacting the wellbeing of EU citizens, gained prominence in 2020 when an estimated 35 million individuals, equivalent to 8% of the population, faced a fundamental struggle to maintain adequate warmth in their homes. Though there was a slight improvement, with the rate decreasing to 6.9% in 2021, 2022 witnessed a notable resurgence, with the rate rising to 9.3% [1]. Energy poverty, characterized by the inability to access affordable, reliable, and secure energy services, is a complex and multidimensional problem. As articulated by Day et al. [2], it can be understood as "*an inability to realize essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy services, and taking into account available reasonable alternative means of realizing these capabilities.*" The EU Energy Poverty Observatory (the predecessor project of the Energy Poverty Advisory Hub) provides a complete definition: "*Energy poverty is a distinct form of poverty associated with a range of adverse consequences for people's health and wellbeing - with respiratory and cardiac illnesses, and mental health, exacerbated due to low temperatures and stress associated with unaffordable energy bills. Energy poverty indirectly affects many policy areas, including health, environment and productivity. Addressing energy poverty can bring multiple benefits, including less money governments spend on health, reduced air pollution, better comfort and wellbeing, improved household budgets, and increased economic activity*" [3]. According to Pellicer-Sifres [4], an adequate definition considers both underlying causes and broader consequences, while offering insights into possible policy interventions.

Energy poverty's severity has been exacerbated by a confluence of factors, including the effects of the COVID-19 pandemic, energy price rises, and geopolitical tensions [5]. The pandemic, in particular, underscored the critical importance of access to basic amenities, such as heating and electricity, as more people spent more time at home [6]. Research conducted by Ambrose et al. [7] delves into the lived experiences of energy-poor households, revealing additional consequences for energy-poor households, mostly linked to limited access to third places and other disruptions to their usual coping strategies. This issue goes beyond individual health and wellbeing [8–11] to have profound implications for economic stability and opportunities, education, and employment prospects [12–14]. Bienvenido-Huertas [15] found that social measures were insufficient to avoid energy poverty during the pandemic lockdown, while Bagnoli et al. [12] analyze the effectiveness of Spain's electricity social rate's impact on energy poverty. Nevertheless, these policies often overlook underlying energy access issues [16], neglecting lasting solutions like energy efficiency and renewable energy systems.

Meanwhile, public institutions are driving investment in renewable energy infrastructure to meet climate needs and international targets, and rooftop photovoltaic (PV) systems have emerged as an important contributor to this transition in cities [17]. A window of opportunity arises here to optimize investments, and policy measures often operate in silos and interact little with each other [18]. The literature illustrates the interplay between energy and social policies. Kyprianou et al. [19] state that energy poverty should be addressed mainly by creating effective policies while encouraging synergies among policies of different fields. The opportunity is to explore the possible synergy between increasing solar roofs in the city, a new policy for which a new budget is required, and reducing subsidies already provided through this substitute good.

In response to these pressing challenges, this study proposes that a shared renewable energy self-consumption system for energy-poor homes is a superior alternative to traditional energy checks. This support model is demonstrated through a case study in València, Spain, encompassing fifty doubly vulnerable households, including elderly individuals experiencing social isolation and loneliness. We aim to uncover economic and environmental benefits by proposing a sustainable approach to integrating energy-poor households into energy communities, thereby contributing to social welfare and the energy transition. Our goal is to optimize policy design and define how to allocate shared energy coefficients among members to create a cost-effective policy. Additionally, we aim to understand the varying energy needs of different consumers and how this translates into concrete policy measures.

The remainder of the paper is organized as follows: section 5.2 discusses the current literature around energy poverty and the two measures to alleviate it discussed in this study, section 5.3 presents the methodology and the mathematical model employed. Section 5.4 describes the case study in València. Section 5.5 shows the results from the analysis, and section 5.6 their implications. Finally, section 5.7 concludes by summarising the paper's main findings.

5.2 The energy poverty challenge for a just energy transition

One of the energy transition challenges is energy justice, a key concept to better-informed energy choices from energy planers and consumers [20]. Research by Belaïd [5] highlights how energy prices and the green transition may exacerbate energy poverty in Europe without adequate policies, creating new inequalities and reinforcing existing ones. Energy efficient or renewable energy technologies are often costly, leading to the exclusion of people who cannot afford to adopt them [21]. Moreover, subsidizing the energy-vulnerable may lead to increased energy use and emissions [22]. Therefore, it becomes evident that interactions between energy poverty and carbon emissions need to be recognized, necessitating a holistic approach to energy transition policies.

The European Energy Poverty Advisory Hub (EPAH), the main hub for expertise on energy poverty in Europe, aims to "eradicate energy poverty while accelerating energy transition". This objective aligns with SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all". The objectives of EPAH and SDG 7 were incorporated into the Clean Energy for All Europeans package in 2019 [23]. The Clean Energy for All Europeans package aims to move consumption toward cleaner energy sources while protecting vulnerable consumers from energy poverty. It encompasses a wide array of measures, including enhancing the energy efficiency of buildings, facilitating the integration of Renewable Energy Sources (RES), and reforming the electricity market structure.

Pye et al. [24] classified EU member state policies into four categories: financial aid, consumer protection, energy savings, and information provision. Their research revealed that approximately 75% of EU member states rely on financial aid as a primary support for vulnerable consumers. Moreover, consumer protection mechanisms are in place in about 80% of these member states to prevent disconnections due to non-payment. The study also emphasizes the considerable scope for improving the degree to which building retrofit measures are targeted to those in need. Another comparative study by Kyprianou et al. [19], covering five EU countries, utilized a similar classification but also included renewable energy systems alongside energy efficiency. Notably, only one of the studied countries (Spain) provides measures for the four categories. Both studies mention that subsidized schemes for promoting energy saving and Renewable Energy Sources (RES) are not usually designed as an energy poverty measure; they include the category because the vulnerable population is occasionally given additional incentives. RES demand high upfront costs, but they will pay off in several years with positive effects in reducing energy poverty [25]. However, this measure assumes that vulnerable populations can provide the remainder of the investment, which is not usually possible in cases of energy poverty. Consequently, as stated by Kyprianou et al. [19], energy poverty should be addressed mainly by creating effective policies while encouraging synergies among policies of different fields.

5.2.1 Energy checks as a solution to energy poverty

Bagnoli et al. [12] analyze the effectiveness of the electricity social rate, the "Bono Social de Electricidad", introduced in 2009 in Spain's electricity market, a policy aimed at increasing electricity affordability by entailing a discount on prices for vulnerable consumers. They found that the policy's introduction effectively reduces the likelihood of energy poverty for eligible households. However, the magnitude of the effect is relatively modest, with only 2% of households escaping energy poverty. Another interesting finding was that it does not alter the quantity of electricity consumed but reacts entirely through a lower expenditure on electricity. The authors proposed two possible interpretations for this finding. First, suppose households do not increase their electricity consumption even though its effective price has decreased despite a decrease in its effective price. In that case, it may be due to electricity being a necessity good. In this scenario, demand was already entirely satisfied before the subsidy, and households do not ration their electricity. The savings from a decreased electricity expenditure could be fully allocated to other essential expenses. The less optimistic interpretation would be that the vulnerable households rationed their electricity consumption before the introduction of the policy and are still rationing their consumption after the policy. Thus, according to Hanke et al., [16], while energy checks can provide short-term relief by identifying households needing assistance and providing one-time financial aid, they do not address the underlying issue of access to affordable energy and do not promote sustainable solutions such as energy efficiency measures and the use of RES, which can help reduce energy costs in the long run.

5.2.2 PV systems and energy poverty

Public institutions are driving investments in renewable energy infrastructure to meet climate needs and international targets, and rooftop photovoltaic systems have emerged as an essential contributor to this transition in cities [17]. However, the energy transition seems to hinder energy affordability. Even if adopting renewable energy is the unique solution to mitigate climate change and reduce its cost, it does not favour energy poverty reduction in Europe [26]. Thus, a fair energy transition must consider specific measures or policies to include the most vulnerable consumers.

The EU must carry out a socially just and equitable transition to a carbon-neutral European Union by 2050 to ensure that no one is left behind and that energy and climate targets are met. One of the best options is to empower citizens by involving them in the energy transition [26]. Furthermore, the profitability of implementing optimally sized PV systems increases when forming REC compared to considering buildings individually [27].

The recast of the Renewable Energy Directive (RED II) [28] highlights REC's social role in energy transition and stipulates "*opportunities for renewable energy communities (REC) to advance energy efficiency at household level and (. . .) fight energy poverty*". RED II further links an enabling framework "*to promote and facilitate the development of renewable energy communities*" with the obligation to ensure the participation of all "*consumers, including those in low-income or vulnerable households*". However, RED II refrains from providing details on achieving RECs' social role in practice. Greece [29], Italy [30], Portugal [31], and Spain [32] link RECs with energy poverty alleviation in their national energy and climate plans. Standal et al. [33] explore the challenges that can be identified for energy justice in RECs from the perspective of potential and existing shareholders and discuss how identified challenges are addressed in the recast Renewable Energy Directive (REDII). Their study concludes that RECs alone have limited capacity to address distributional imbalances. It is up to the states and individual RECs to find appropriate ways in which the aspiration for local benefits, combined with the philosophy of democratic governance, can help to reconcile, at least in part, financial, social and other inequalities.

Despite institutional guidelines linking renewable energies with social justice and even referring to it as a solution to energy poverty, policies and aids for implementing these systems are not connected with policies and aids to energy poverty. They are usually focused on consumer protection policies, energy checks, and subsidized schemes for energy efficiency and the use of renewable technologies [19].

Some scientific literature supports the link between energy policy and social policy. According to a study conducted in the United Kingdom [34], community solar PV appears to favour areas of higher deprivation, implying that community groups advocating for solar PV installations have successfully delivered feed-in-tariff benefits to low-income communities. Moreover, according to Primc et al., providing universal access to modern energy infrastructure developed nationally requires significant investment. However, this cost can be somehow compensated for the decrease in the amount granted each year through social support [35].

5.3 Methodology

To conduct this research, we followed the methodology described in 5.3.1. The starting point is the computational model of the operation of a REC that we have developed in previous projects and explained in papers such as [36, 37]. The model allows the input of the different load curves of the dwellings that will form the REC. The first phase is data collection, where we obtain information about the generation, consumption and electricity price. We use metered hourly electricity consumption data from vulnerable households for one year, accessed via smart meters. Spanish government forces vulnerable dwellings to get the regulated electricity bill to access public subsidies. Thus, we used the public electricity price of the regulated tariff for this work. The simulation software PVSyst [38] provided the hourly photovoltaic system capacity factors for the case study solar installation.

Optimizing the REC is the next phase once we have gathered all the data. The energy sharing of the REC uses static coefficients, meaning that the sharing rates among all households remain constant all year. This allocation method is more manageable for public authorities to implement and for energy users to understand while not significantly worsening the financial results [36, 39]. The objective of the optimization is to minimize the electricity bills of the REC as a whole. Therefore, households will not necessarily all save the same with this scheme, and those whose consumption matches better to energy generation will experience more significant bill reductions. The REC optimization is run considering a range of PV system capacities to identify several potential sizing recommendations.

Finally, we measured each scenario's Net Present Value (NPV) for 20 years of operation. The savings are those of the public institution, instead of the household bill reductions, as they undertake the investment. We selected the best NPV obtained that guaranteed the same level of service as the electricity social rate and compared them. Hence, we measured the schemes regarding financial results for the public institution, bill reduction and overall benefit for the vulnerable users.

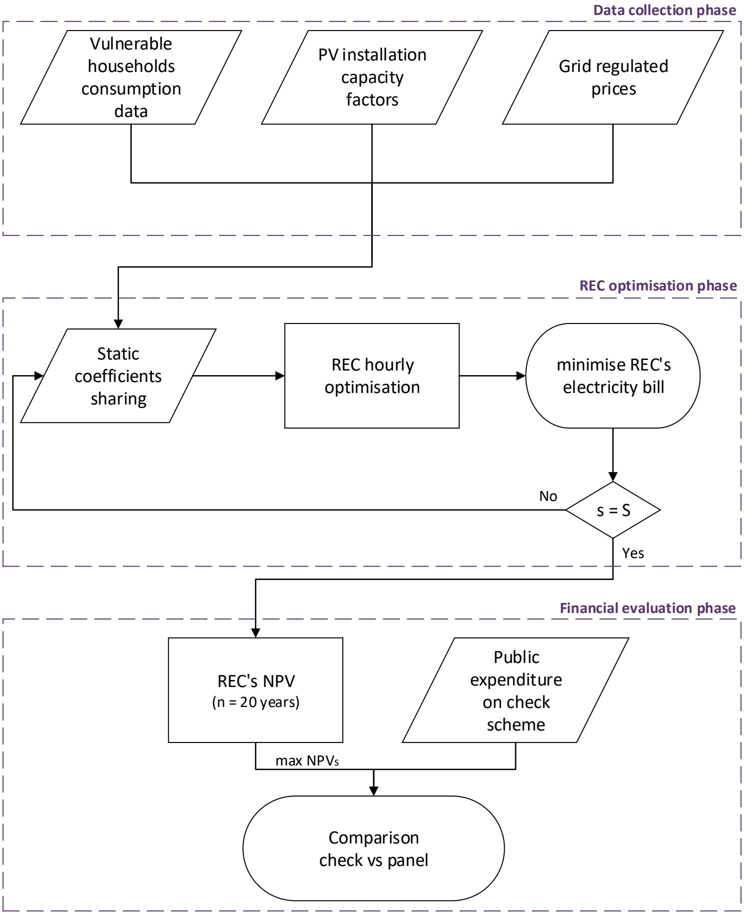

Figure 5.3.1: Methodology workflow.

5.3.1 Mathematical model

We define the mathematical model in this section, including the REC operation, how electricity gets billed from the grid and the financial evaluation. First, the objective of the optimisation function is to minimise the costs (C^G) that households belonging to the REC pay for electricity.

All the power generated in the REC must be appropriately allocated to a consumption point or fed into the grid. Thus, at every moment, the power generated (P_t^{PV}) is the product of the nominal power (P_{nom}^{PV}) with the capacity factor (CF_t), 5.3.1. Similarly, the hourly power allocated to each household ($P_{j,t}^{A}$) is the product of the power generated and the allocation coefficient ($\beta_{j,t}$), 5.3.2.

Nevertheless, the allocated power to a household will rarely match the demand. Hence, in case of surplus, as expressed in 5.3.3, although part of the allocated energy will be self-consumed ($P_{j,t}^{SC}$), another part can be fed into the grid by selling ($P_{j,t}^{SELL}$) or giving it away ($P_{j,t}^{GIFT}$) as the excess PV generation sales are capped to keep the bill positive. In other cases, we may face a power deficit, and the REC has to purchase ($P_{j,t}^{PUR}$) some power from the grid to meet the demand ($P_{j,t}^{D}$), 5.3.4.

The sum of the allocation coefficients of all households must always be one, 5.3.5. Besides, we use static coefficients to develop this work. These coefficients are constant throughout all years for each point of consumption, meaning that the power-sharing is performed as though each household has a dedicated portion of the community PV system.

$$P_t^{PV} = P_{nom}^{PV} \cdot CF_t \qquad \forall t \in T \tag{5.3.1}$$

$$P_{j,t}^{A} = P_t^{PV} \cdot \beta_{j,t} \qquad \forall t \in T, j \in J \tag{5.3.2}$$

$$P_{j,t}^{A} = P_{j,t}^{SC} + P_{j,t}^{SELL} + P_{j,t}^{GIFT} \qquad \forall t \in T, j \in J \tag{5.3.3}$$

$$P_{j,t}^{SC} + P_{j,t}^{PUR} = P_{j,t}^{D} \qquad \forall t \in T, j \in J \tag{5.3.4}$$

$$\sum_{j=1}^{J} \beta_{j,t} = 1 \qquad \forall t \in T \tag{5.3.5}$$

The electricity bill and the financial indicators are obtained as indicated in 5.8.1 and 5.8.2, respectively. The savings for the public entity are the difference between the initial economic support and the support once the REC is established. The initial economic support is the annual cost of electricity purchased from the grid multiplied by the percentage of the bill covered by the energy check or electricity social rate. Once the REC is established, the public entity will cover the difference if any household's savings fall short of achieving the same savings as in the initial case with the social rate. This covering will be a direct bill reduction as it is currently done with the electricity social rate.

5.4 Case study

5.4.1 Spanish energy poverty framework

In 2019, the Ministry of Ecological Transition of Spain established the National Energy Poverty Strategy 2019-2024 [40], which implements the mandate set out in Article 1 of Royal Decree-Law 15/2018 of 5 October on urgent measures for the energy transition and the protection of consumers. For the first time, the Strategy defines the situation of energy poverty and vulnerable consumers, diagnoses the situation in Spain, determines lines of action, and sets targets for reducing this social problem that affects more than 3.5 million people in the country.

The Strategy includes measures at the palliative and structural levels, with short, medium, and long-term actions. The aim is not to make financial aid measures the main policy action but rather transitional instruments. This framework proposes measures in the four categories mentioned in section 5.2: financial aid, consumer protection, energy efficiency, and information provision. Regarding the structural and energy efficiency measures, the Strategy states that it requires a thorough knowledge of the situation of households and their shortcomings, how to approach these, and how to focus these actions on achieving the best cost-benefit ratio. In other words, the best possible results should be obtained with the least necessary investment. The Strategy also refers to promoting photovoltaic self-consumption among medium-long-term measures. The final objective of the implementation of these measures within this Strategy is to increase the comfort of vulnerable consumers, especially concerning shared self-consumption and the possibility of management of the installations by third parties, which would enable end users to benefit from savings in their energy bills without having to get involved in the specific tasks of project management.

Among the proposals in the Strategy, the most significant specifications are given for consumer protection, emergency measures to avoid supply cut-offs, and the

Electricity and Thermal Social rate. To receive it, one must have contracted the voluntary price for the small consumer, which means being in the regulated market and meeting specific requirements associated with income or the type of family unit. The aid ranges from a 25% discount for vulnerable consumers to a 40% discount for severely vulnerable consumers. Exceptionally, until June 30, 2024, these discounts were increased to 65% for vulnerable consumers and 80% for severely vulnerable consumers, according to Royal Decree-law 18/2022 [41] and its extension in Royal Decree-law 8/2023.

Regarding the electricity social rate, from the very beginning, it was considered that this aid should be paid within the electricity market itself, falling on the vertically integrated companies, i.e. those that not only sell energy but also produce and distribute it. The amounts collected go to the regulated retailers who apply the discounts. In this way, their loss of income is compensated. The details of this method of financing have always been controversial, as evidenced by the successive appeals lodged by the companies, which have led to three changes in the system in eight years. First, from 2014 to 2016 (Royal Decree-Law 216/2014), the companies that, in addition to trading energy, also produce and distribute assumed this cost. However, the mechanism was declared unconstitutional, making it necessary to return the amounts they had paid and change the system. From 2016 to 2022 (Royal Decree-Law 7/2016) [42], only the retailers had to assume this cost depending on the number of customers they had. This was particularly disadvantageous for retailers focused on domestic customers, as they had many contracts but with small supplies. On the other hand, it benefited those working with large customers.

Once again, some retailers lodged an appeal against this model, and it was admitted, so now this financing model cannot be applied because it discriminates against them. A new financing model was therefore necessary. From April 2022 (Royal Decree-Law 10/2022) [43], the cost of the social bonus must be paid by all the actors in the electricity sector (generation, transmission, distribution, and commercialization companies). In the specific case of the retailers, the amount must be paid according to the number of customers of the company. Bagnoli et al. [12] state that this financing scheme seems unlikely without involving any public funds, and they suggest two options. One is that the policy could have had a fiscal cost, probably in terms of foregone fiscal revenues through lower tax rates. The other possibility is that other consumers could have financed the policy through cross-subsidies.

5.4.2 Spanish REC framework

Spain introduced the concept of shared self-consumption in Royal Decrees 244/2019 [44] and 23/2020 [45] after eliminating the controversial self-generation legal framework, which discouraged self-consumption by setting very restrictive and economically detrimental conditions for such installations. The Royal Decree 244/2019 introduced a compensation mechanism for prosumers with installed power until 100 kWp, establishing an offset price for self-consumption surpluses supplied to the national grid. In 2020, the Royal Decree 23/2020 introduced the concept of REC into Spanish regulation. This regulation established that REC members should be within 500 meters of the generation point, and the generated power should be allocated employing coefficients fixed in time. This limited distance was later increased to 2000 meters with the Royal Decree 20/2022 [46].

5.4.3 Data and context of the selected citizens

In this context, we propose the implementation of a public REC as a long-term solution to address energy poverty among vulnerable consumers. We aim to compare this alternative with the subsidies to determine its suitability in the medium to long term, particularly for cases where institutional support is needed beyond one-time emergency assistance. To investigate the feasibility and effectiveness of our proposal, we conducted a case study focusing on a simulated shared self-consumption system involving 50 vulnerable households in Valencia, Spain. The prevalence of energy poverty in the city is a significant concern, with 23.1% of households, amounting to more than 85,000 households, experiencing this issue, as indicated by the energy poverty map of Valencia [47]. Approximately 10,000 face Social Isolation and Loneliness (SIL) among these households, as determined through surveys and data from the city council's social services [48].

In the city of Valencia, any household has the potential to participate in an energy community, highlighting the inclusive nature of our proposed REC. Moreover, Valencia has shown a remarkable commitment to achieving climate-related objectives, exemplified by its designation as the European Green Capital for 2024. Additionally, the European Union has chosen the city to participate in the "One Hundred Smart and Climate Neutral Cities by 2030" mission, further underscoring its dedication to sustainable and environmentally friendly practices. By studying the implementation of a REC in the context of Valencia's energy poverty and commitment to sustainability, we aim to contribute to the broader understanding of effective strategies to address energy poverty and promote REC.

The study focuses on 50 households that can be classified as doubly vulnerable. These households primarily consist of elderly individuals who encounter challenges in meeting their energy expenses, maintaining adequate indoor temperatures, and experiencing Social Isolation and Loneliness (SIL). SIL is a serious public health risk that affects a significant portion of the older adult population, according to the USA National Academies of Sciences, Engineering, and Medicine (NASEM). The 2020 NASEM report also recommended using tailored community-based services to address SIL in older adults. However, there is a lack of evidence to identify the most effective interventions [49].

Moreover, elderly households are particularly vulnerable to energy poverty due to low annual income and higher electricity costs [50]. Based on the data provided by the families, we considered these households as severely vulnerable consumers. Therefore, it is considered a requirement that the savings obtained with the REC are at least equivalent to the 40% discount of the electricity subsidy for severely vulnerable consumers.

To simulate the self-consumption system, we gathered hourly electricity consumption data for the year 2021 from the 50 households mentioned above. The households have consumption levels below the average for Valencia during the same period, recorded as 2518 kWh/year per household. The consumption of the 50 households was acquired thanks to the participation of these households in the project "Energía social y confort en el hogar: retos mayores" (ESM) funded by the Innovation and Knowledge Management Department of the City Council of València and represents a sample of the elderly people in a vulnerable situation regarding SIL and energy poverty.

For simplicity, the PV system is assumed to be a centralized plant without specific roofs representing the installation points. A previous study indicated that photovoltaic roofs could be up to 64 kWp in public buildings and 92 kWp in commercial/industrial buildings in Valencia [51]. However, there are already PV installations in public buildings up to 100 kWp [52]. For this study, up to 100 kWp of PV, equivalent to 2 kWp per household, has been considered to capture the full range of rooftop installation potential. Nevertheless, the methodology is applicable to lower power constraints. We considered an azimuth of 0° degrees and a tilt angle of 40° degrees. The hourly capacity factors are generated with

PVSyst [38]. The system yields 1,622 kWh/kWp annually, which is scaled for the parametric sizing study from 1 to 100 kWp.

The investment depends on the size of the plant and its lifetime, so we have used the price scale in Table 5.4.1, provided by the regional government [53].

Table 5.4.1: Reference cost for PV systems (Source [53]).

Power range	Reference cost
P <= 10 kWp	1.600 € /kWp
10 kWp <P <= 20 kWp	(1.800 – 20 * P) € /kWp
20 kWp <P <= 50 kWp	(1.566 – 8,33 * P) € /kWp
50 kWp <P <= 500 kWp	(1.178 – 0,556 * P) € /kWp

We assume 20 years of operation, inverters and other electronics are replaced after ten years, while PV panels last for the 20 years the study covers. Based on the benchmark, the price range considered for replacing inverters varies linearly between 737 € (for 1 kWp) and 7,534 € (for 100 kWp). In addition, the operation and maintenance costs are calculated [54] as 20.60 € /kWp/yr. Since the government is not a profit-seeking stakeholder, the nominal discount rate is 2% to match expected long-term inflation.

Finally, we use the year 2021 to study this particular case as the demand data is from it. During 2021, the price of purchased electricity fluctuated between 0.077 and 0.270 € /kWh, including the commodity and grid charges, while the price of selling electricity fluctuated between 0.048 and 0.206 € /kWh [55–57]. Besides, the fixed part of the electricity price depends on the contracted power, which is 32.10 € /kW/year [56, 57].

5.5 Results

In this section, we present a comprehensive analysis of the outcomes derived from the proposed integration of vulnerable households into a REC compared to the payment of the electricity social rate. The review is structured in three key subsections. First, in ‘5.5.1 Overall results’, we address the main question of "Panel or check?" by demonstrating the economic advantages of integration into a REC, showing net savings for different photovoltaic (PV) capacities. Secondly, ‘5.5.2 Individualized results’ delves into the distribution of savings for each household in different scenarios, providing information on the nuanced impacts of REC implementation. Finally, the ‘5.5.3 Analysis of savings distribution’ examines histograms of relative savings in specific REC scenarios, unravelling the complexities of savings patterns across different installation capacities. Together, these subsections provide a detailed understanding of the economic implications and individualized benefits of the proposed REC integration.

5.5.1 Overall results

Addressing the main question "Panel or check?", the proposed integration of households into a REC, compared with the payment of the electricity social rate, proves economically advantageous in terms of public expenditure, securing net savings for all capacities up to a 75 kWp plant, as shown in Figure 5.5.1 with the NPV for all PV capacities in 20 years. Three capacities stand out for a more detailed investigation; the first is 31 kWp, which results in the maximum NPV at 58,500 € and a simple payback time of 6.3 years. Next is 58 kWp, which is where the need for supplemental economic aid to secure savings of up to 40% of the electricity cost is eliminated, requiring no energy checks. Here, the NPV is 22,500 € with a simple payback time of 14.1 years. The third is 75 kWp, the maximum installation capacity possible using the current energy poverty budget. Installations above 75 kWp have a negative NPV.

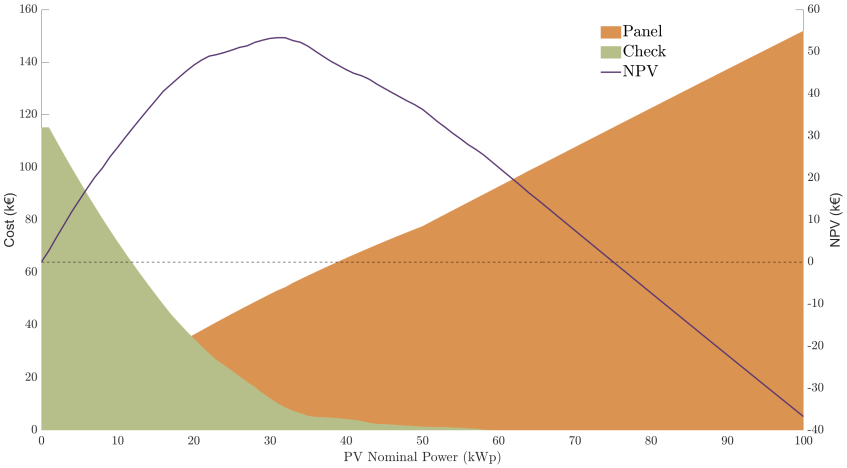

Figure 5.5.1: Performance of the panel policy compared to check policy in 20 years.

Figure 5.5.1 also depicts the cost of the energy checks solution (check) and the cost of the installation (panel) as a function of nominal power. For the baseline scenario (0 kWp), where there is no REC, the public expenditure after 20 years is 115,245 € . The annual public expenditure is 7,048 € /year, or 141 € per household (on average). Since it is a condition that all households experience a minimum 40% reduction in their energy costs, aligning with the electricity social rate, the higher the installed PV capacity, the lower the annual public expenditure to support these households. With more savings from the REC, households need less financial support through checks. Beyond an installation of 58 kWp, households no longer require energy checks, and the cost of the REC in 20 years remains below cost only with checks in that period. At 75 kWp the cost of the installation reaches the cost without REC, i.e. the NPV reaches zero. It can also be seen that there is an elbow in the rate of cost reductions in checks at approximately 35 kWp, at which point 95% of the check costs have been reduced. This elbow is due to the saturation of self-sufficiency as the mismatch of supply and demand limits the greater economic potential of self-consumption.

Expanding on the earlier discussion, Figure 5.5.2 and Figure 5.5.3 provide more insights into how the energy system behaves with different PV system capacities. Transitioning from the 31 kWp to the 58 kWp scenario, there's an increase in self-consumption, less energy bought, and more available to share or sell. However, with the 75 kWp scenario, the energy sold and given away increases again, while self-consumption drops slightly. This slight reduction in self-consumption, in exchange for more energy sold and given away to the grid, results in greater savings. The monthly energy balance for the 58 kWp scenario shows differences throughout the year, with a significant increase in energy purchases in January and more energy left over to give away as the installation's power increases, especially during the hot season.

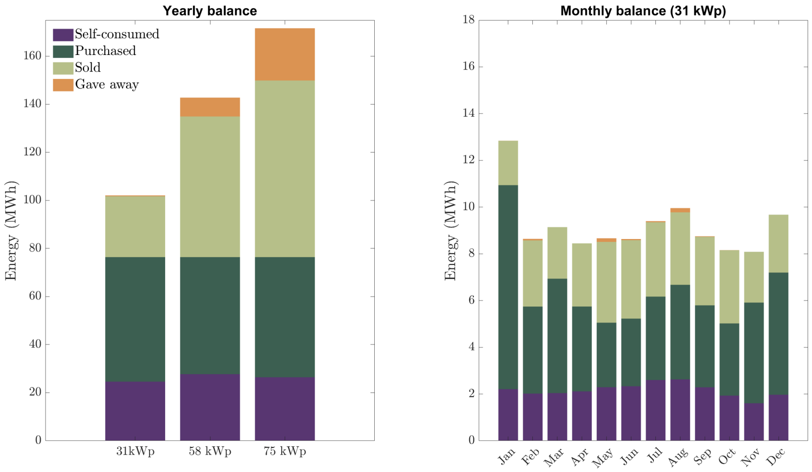

Figure 5.5.2: Annual energy balance and monthly energy balance for 31 kWp.

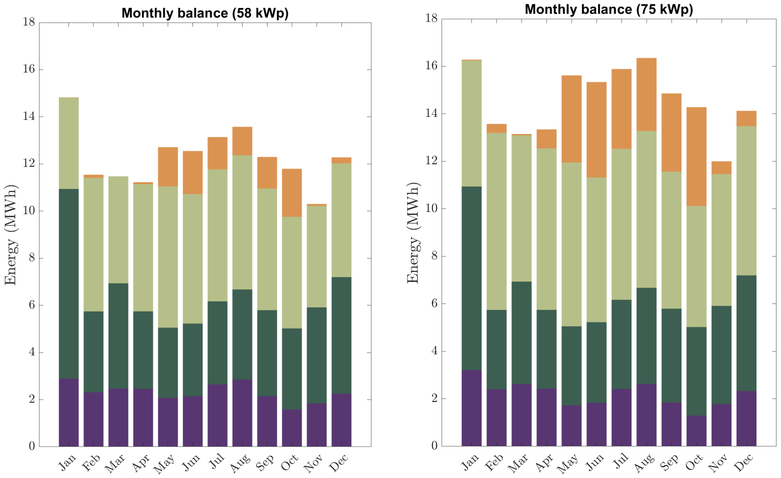

Figure 5.5.3: Monthly energy balance for 58 kWp and 75 kWp.

5.5.2 Individualized results

As explained in section 5.5, this study has hourly electricity consumption curves for the year 2021 for each of the fifty households. The least favoured profiles have consumption peaks in winter and dark hours when no generation exists (the seasonal profiles can be found in 5.8.3).

The differences between the three scenarios in savings can be observed by analyzing the relative economic savings for the fifty households with the REC compared to the current social electricity tariff. In the 31 kWp case, the average savings from the REC is 149 € per household on average, as compared to 141 € per household for the checks. While most households receive similar benefits, extreme cases can result in 182.4% REC support or as low as 34.2% compared to the energy checks. For the 58 kWp installation, where all households save at least 40% on electricity costs from the REC, the average household support increases to 232 € . In the scenario with an installation of 75 kWp the average household savings rises to 256 € . The relative savings for each household in the three scenarios can be found in 5.8.3.

5.5.3 Analysis of savings distribution

To delve deeper into this analysis, Figure 5.5.4 presents the relative savings histograms for the three scenarios. On the vertical axis, frequency represents the number of households for which the relative saving represented on the horizontal axis occurs. The horizontal axis represents the savings obtained with the REC compared to those obtained with the electricity social rate. A relative saving of 1 means the same savings are made with the electricity social rate as with self-consumption. A lower relative saving means less than 40% is saved with self-consumption, still needing an energy check, and vice versa.

Relative savings increase as power increases, at the same time the range is reduced. The 31 kWp installation shows the greatest range in household savings, with the least benefited households receiving 0.4 and the most benefited receiving 1.8, a range of 1.4. The range is narrower in the 58 kWp and 75 kWp cases, at 1.0 and 0.9, respectively. The 58 kWp scenario shows less difference in frequency between the most common savings, 1.6 and 1.8, and the rest. In addition, the distribution of the remaining household savings is more uniform. The 75 kWp scenario shows that the higher the power, the higher the savings for most households.

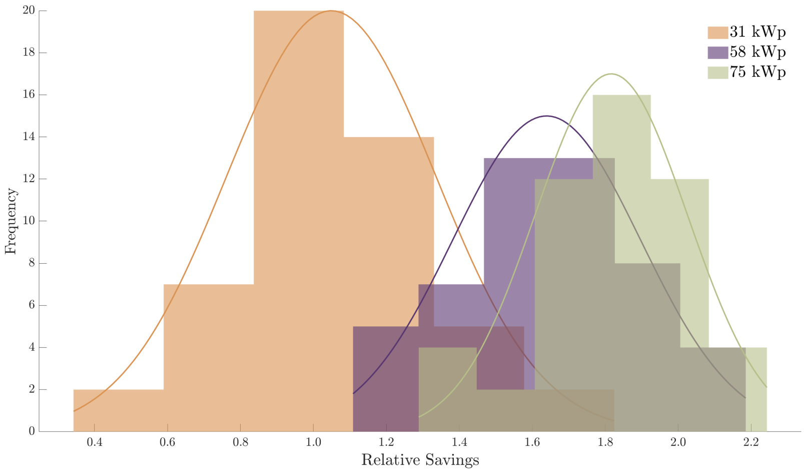

Figure 5.5.4: Histograms of relative savings and frequency for three scenarios.

Figure 5.5.5 shows the dispersion of the generated power allocated to each household to their annual energy demand. This graph shows a clear relationship between demand and allocated power by the energy community; therefore, the simulation model responds to the community's needs and does not arbitrarily favour some households over others.

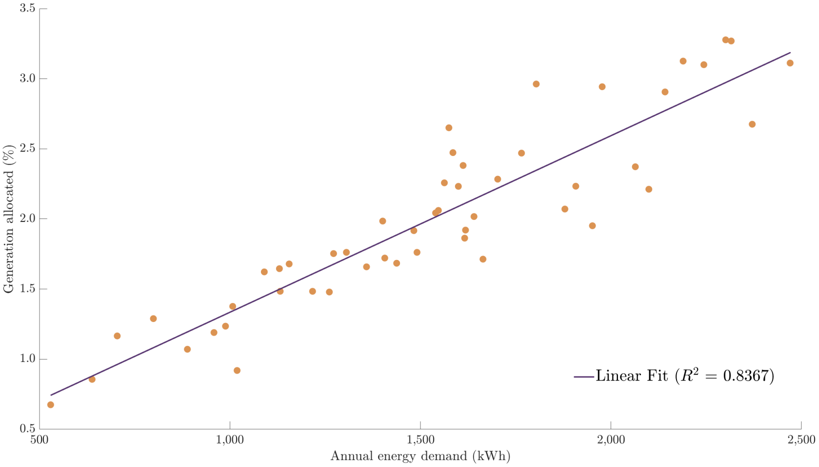

Figure 5.5.5: Dispersion of allocated power generated depending on annual energy demand.

We were also interested in understanding what behaviours led to higher savings in some households versus others. Our initial hypothesis is that the most significant savings would occur in households with higher electricity consumption during peak price hours and with PV generation as they would self-consume in the most expensive hours. Peak hours in the Spanish electricity tariff system are from 10.00 to 13.00 and 18.00 to 21.00 on weekdays [58]. Figure 5.5.6 shows how these variables relate and show linearity while the demand is not too high. However, increasing the demand does not imply higher savings once the energy demand surpasses 300 kWh in those hours. We interpret this shift to occur because the constraint in the relationship changes from demand to generated power. As a result, we have to purchase electricity from the grid to cover part of that demand during expensive hours.

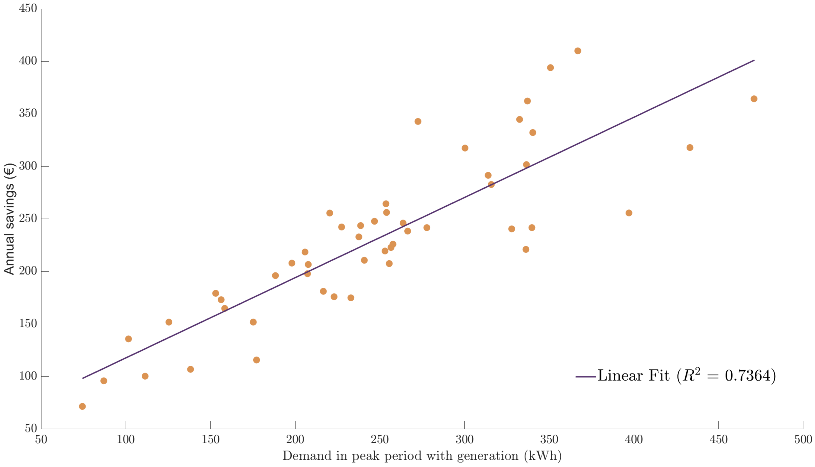

Figure 5.5.6: Dispersion of economic savings depending on energy demand during peak hours with generation.

5.6 Discussion and policy implications

The optimal installation approach varies, depending on whether the goal is to enhance overall efficiency or secure substantial household savings. If the focus is on economic optimization, not every household can attain savings comparable to those offered by the electricity social rate. Consequently, the REC falls short of entirely replacing checks. While increased installation power correlates with higher household savings, it may result in negative Net Present Values (NPV). An intermediate solution targets installations where all households achieve savings equivalent to the electricity social rate. However, this assumes that these households maintain their current consumption levels, overlooking the potential for increased consumption to enhance comfort. Notably, Bordón-Lesme et al. [59] suggest that, for low-income consumers, the rebound effect might occur, albeit to a lesser extent than for higher-income consumers.

Even if consumption does not rise, solving these households' issues remains uncertain. As highlighted by Bagnoli et al. [12] in the context of the electricity social rate, economic relief may not eradicate the rationing of electricity consumption. The REC offers an advantage over the social bonus by optimizing savings through a shift in consumption to the installation's peak energy generation hours. Besides, solar-powered RECs will be better suited to reduce energy poverty related to heat levels, especially in Mediterranean climates, as generation perfectly matches hours of the largest energy needs.

A uniform distribution proves suboptimal in addressing households' varying optimal powers and consumption profiles. Instead, establishing distribution coefficients, subject to annual review based on consumption variations, ensures a tailored approach for each household, as shown in Figures 5.5.5 and 5.5.6.

Additionally, other boundary conditions influence this decision. While in a rural environment, there is typically more space for panel installation, in an urban environment, space tends to be scarcer, leading to the decision to use all available space for rooftop installation. In such cases, it may be more interesting to install the maximum allowed by available space, e.g., 100 kWp in the case study, even if it may not be economically advantageous. In this way, the plant would allow the growth of electricity demand by households, which is expected since they consume below average due to their low income. It would allow other users to join if there is excess electricity. Furthermore, in the worst case scenario, the plant sells electricity with very low emissions in its life cycle (approximately 40 g/kWh according to [60], which replaces electricity from the grid, which has higher emissions per unit of energy (approximately 200 g/kWh according to [61]).

5.7 Conclusions

Our study investigates a specific solution through a REC to alleviate energy poverty. Our results reinforce Primc et al.'s assertion [35] that while gaining access to renewable energy infrastructure demands a significant investment, this cost can be offset by the difference in annual social support provided. The REC, designed for long-term vulnerable consumers, emerges as a tangible solution that substitutes traditional energy checks and aligns with the objectives outlined in institutional guidelines.

The fifty households can be classified as doubly vulnerable. These households primarily consist of elderly individuals who encounter challenges in meeting their energy expenses, maintaining adequate indoor temperatures, and experiencing feelings of SIL. To simulate the self-consumption system, we gathered hourly electricity consumption data for the year 2021 from these fifty households, which have consumption levels below the average for Valencia during the same period.

The results show that participating in RECs is a better economic option for public institutions than paying energy subsidies. At the economically optimal sizing of 31 kWp, the cost of subsidizing energy would be reduced by 58,000 € . At 58 kWp, the need for additional support checks to top up undersupported households disappears, however at a lower NPV of 22,500 € . The largest possible system without incurring additional cost is 75 kWp, which on average increases the electricity cost reduction to 70%. These extra savings would not have been possible in the initial situation with the energy check. Nevertheless, the investment has a lower or equal cost for the public administration in the medium term.

Our results underscore that the REC surpasses the efficacy of traditional energy checks, marking a transition towards renewable energies that is not only fair but also inclusive. Seamless integration of renewable energy sources significantly contributes to alleviating energy poverty among vulnerable households, exceeding the impact of conventional energy checks. Crucial elements include optimal installation distribution, adaptation to variable consumption profiles, and consideration of specific boundary conditions.

CRediT authorship contribution statement

Isabel Aparisi-Cerdá: Writing - original draft, Methodology, Visualisation, Data Curation. Álvaro Manso Burgos: Methodology, Software, Data Curation, Writing - original draft. David Ribó-Pérez: Conceptualization, Writing - review & editing, Supervision. Nelson Sommerfeldt: Writing - review & editing. Tomás Gómez Navarro: Conceptualization, Supervision, Writing - review & editing.

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5.8 Appendix

5.8.1 Electricity billing

The cost of the purchased electricity from the grid (C^G) is the sum of the variable costs incurred during the year (C_t^V) and the contracted power cost (C^{POW}), 5.8.1. On the one hand, the variable costs are calculated hourly as the difference in the price of electricity purchased (C_t^{PUR}) and sold (C_t^{SELL}) to the grid, 5.8.2, where π is the price per kWh to sell or purchase electricity. On the other hand, the contracted power cost is the product between the contracted power (POW_j) and the price per contracted kilowatt (POW_j), 5.8.3.

Excess PV generation sales are capped, as the bill must be positive. Therefore, 5.8.4 determines that the price of electricity purchased (where π_t^{PUR} is the price per kWh of purchased electricity) must be equal to or higher than the price of electricity sold (where π_t^{SELL} is the price per kWh of sold electricity) in each billing period from b_0 to b_f. In the case of generating more surplus than the REC can sell in a given month, it will give it away to the grid for free.

$$C^G = \sum_{t=1}^{T} C_t^V + C^{POW} \tag{5.8.1}$$

$$C_t^V = C_t^{PUR} - C_t^{SELL} = \sum_{j=1}^{J} P_{j,t}^{PUR} \Delta t \pi_t^{PUR} - P_t^{SELL} \Delta t \pi_t^{SELL} \tag{5.8.2}$$

$$C^{POW} = \pi^{POW} \sum_{j=1}^{J} POW_j \tag{5.8.3}$$

$$\sum_{t=b_0}^{b_f} P_{j,t}^{PUR} \pi_t^{PUR} \geq \sum_{t=b_0}^{b_f} P_{j,t}^{SELL} \pi_t^{SELL} \tag{5.8.4}$$

5.8.2 Financial evaluation

We determine the economic performance of the REC through the Net Present Value (NPV). Equation 5.8.5 defines REC's NPV of each year as the subtraction of operation and management (NPV^{OM}) and investment value (PV^{INV}) in that year to the value of the savings (NPV^{SAV}). Equations 5.8.6, 5.8.7 and 5.8.8 define the NPV of saving, operation and management and investment every year, respectively (where SAV is the annual billing savings generated by the REC, d is the market discount rate and OM is the operation and maintenance annual expenses).

The savings for the public entity that carries out the solar installation are due to not supporting the electricity bills in these households. The annual total save is the sum of the savings due to each household (SAV_j), 5.8.9. Meanwhile, we measure the annual savings produced in each household using the 5.8.10 as the difference in the initial economic support and the support once the REC is established. The initial economic support is the annual cost of electricity purchased from the grid in the initial case multiplied by EC, the percentage of the bill covered by the energy check or electricity social rate. Ideally, once the REC is established, these households will not require more economic support to reduce their bills as with the social rate. However, we considered that if any household's savings fall short of achieving this minimum saving (if they do not achieve at least the same savings as in the initial case with the social rate), the public entity will cover the difference. This covering will be a direct bill reduction as it is currently done with the electricity social rate. Thus, we guarantee that the service offered by the public entity is at least as extensive as in the initial situation, implying a net reduction of the savings expected by the public administration. This covering is the subtractor in the equation 5.8.10.

$$NPV_n^{REC} = NPV_n^{SAV} - NPV_n^{OM} - NPV_n^{INV} \tag{5.8.5}$$

$$NPV_n^{SAV} = \frac{SAV}{d}\left[1-\left(\frac{1}{1+d}\right)^n\right] \tag{5.8.6}$$

$$NPV_n^{OM} = \frac{OM}{d}\left[1-\left(\frac{1}{1+d}\right)^n\right] \tag{5.8.7}$$

$$NPV_n^{INV} = NPV_{n-1}^{INV} + \frac{INV_n}{(1+d)^n} \tag{5.8.8}$$

$$SAV = \sum_{j=1}^{J} SAV_j \tag{5.8.9}$$

$$SAV_j = EC \cdot C_0^G - max(0, C_{REC}^G - (1-EC)C_0^G) \tag{5.8.10}$$

5.8.3 Additional figures

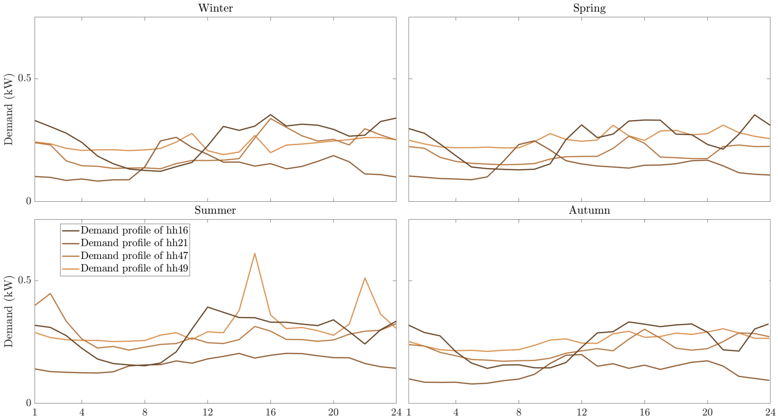


Figure 5.8.1: Demand profiles of the profiles most favoured by REC installation.

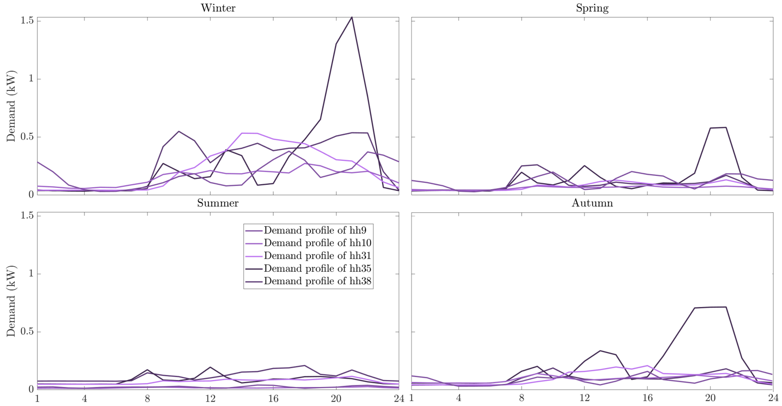
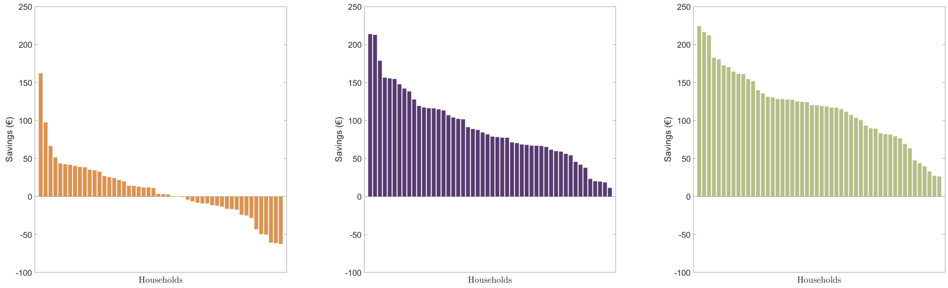


Figure 5.8.2: Demand profiles of the profiles least favoured by REC installation.



(a) 31 kWp REC. **(b)** 58 kWp REC. **(c)** 75 kWp REC.

Figure 5.8.3: Comparison of household savings with a REC and with energy checks.

Chapter 6

General discussion of the results

This thesis focuses on developing methodologies for planning a fair and sustainable energy transition in urban areas, addressing both technical and social aspects. To this end, four interconnected studies, corresponding to Chapters 2 to 5, provide varied proposals for addressing the challenges of the energy transition in cities with an integrated and holistic approach to addressing the multiple challenges of the energy transition in cities from the analysis macro in Chapter 2 to the proposal of a specific solution of Chapter 5.

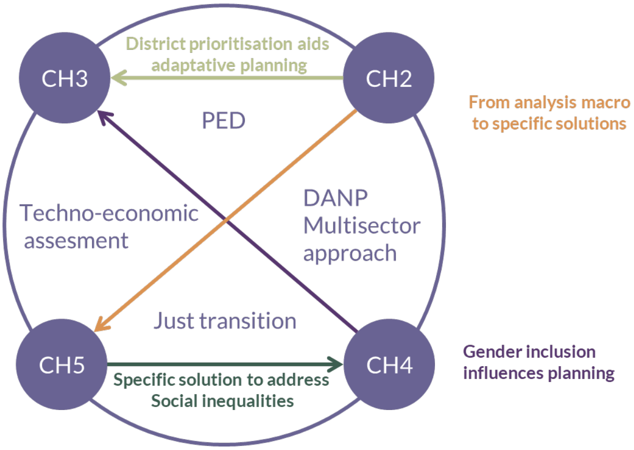


Figure 6.0.1: Chapter interconnections.

Research conducted in Valencia has drawn conclusions that can guide urban planning and public policies towards a more sustainable and equitable future. Valencia has proven to be a relevant case study due to its proactive approach and comprehensive planning towards climate neutrality. The city's commitment to reducing carbon emissions, promoting renewable energy, and enhancing social equity makes it an ideal setting for testing and validating new methodologies. Close collaboration with various stakeholders, including policymakers in Valencia, illustrates that the methodologies and strategies developed in this thesis are applicable in practice and can address the city's specific needs.

The first chapter focuses on applying the DANP methodology for district prioritisation, using Valencia as a case study. This methodology allows for a comprehensive evaluation of various criteria, including technical, social, urban, environmental, and economic factors. This study identified and prioritized the districts in Valencia with the greatest potential to become PED. The methodology allows for identifying why certain criteria are prioritised over others, offering a clear understanding of the factors that drive these decisions. For example, economic criteria like investment and grants emerged as highly influential because they directly impact the feasibility and success of urban energy projects. The methodology also clarifies why certain districts were prioritised, with areas on the city's outskirts, such as Poblats Marítims, highlighted due to their high potential for building retrofitting and strong community interest in energy initiatives.

This prioritization is useful because it directs resources and efforts towards areas with the highest potential impact, ensuring an efficient and targeted approach to urban energy planning. The proposed methodology also facilitates resource savings by allowing for phased planning; for example, advanced districts can be transformed first, while less developed areas can be prepared for future transformations by improving the relevant criteria. Furthermore, the methodology effectively addresses common challenges in strategic planning, such as the lack of information and uncertain data, by providing a robust framework for informed decision-making in urban energy transition. The methodology allows working with a limited number of criteria concerning all the criteria that may interest this decision-making. However, the methodology also allows for adapting the criteria to be considered in each case study through a validation process with local experts.

This prioritization analysis not only provides a solid foundation for the second chapter but also sets the stage for addressing the broader challenge of planning the transformation of urban districts. Building on the insights gained from the prioritization, the second chapter focuses on the specific energy planning of the prioritized districts, with the Marina of Valencia, the UWF located in Poblats Marítims, serving as a case study. Within this context, three strategic scenarios were analyzed to assess their potential to achieve the Positive Energy District (PED) target. Each scenario successfully meets this goal, with an excess energy production over consumption ranging from 2,728 MWh/yr to 7,943 MWh/yr, highlighting the feasibility and impact of the proposed strategy.

The proposed methodology is designed to tackle this complex and transformative challenge. Given the multifaceted objectives of the energy transition, a multidisciplinary approach to planning is essential. The execution and evaluation of the plan must also be multidisciplinary, ensuring coherence across different sectors and objectives. The planning process is also inherently adaptive, allowing adjustments to respond to emerging threats and opportunities. This adaptability is crucial for maintaining the relevance and effectiveness of the plan over time. Therefore, it is essential to plan for continuous monitoring as well as preventive and adaptive management of changes. This includes establishing processes to identify and address potential risks and opportunities as they arise, ensuring that the plan remains responsive and aligned with its objectives.

Indicators, especially KPIs, play a critical role in this management process, and they must be multidisciplinary to reflect the diverse objectives of the transformation adequately. Furthermore, it is crucial to recognise that the planning framework is not static; it evolves continually to reflect new information, shifts in objectives, and changes in available resources, activities, costs, and timelines. This dynamic approach also extends to elements such as SWOT analyses, audits, and risk assessments, ensuring the strategies remain robust and effective throughout their implementation. In this way, the proposed methodology directly addresses the challenge of planning for transformative change, offering a structured yet flexible approach that evolves with the project.

The methodology applied to a UWF in Valencia allows adaptation to different contexts and district typologies. Tailoring the planning process to the unique characteristics of each district ensures that the strategies are not only effective but also sustainable and inclusive. However, residential districts present greater complexities in relation to the governance and inclusiveness of their residents. They will require steps prior to this methodology to ensure the appropriate selection of criteria and actions to be implemented.

The third chapter addresses the intersection of social inclusion and energy transition by introducing a gender perspective into energy transition policies. While social inclusion does not automatically result from decarbonisation efforts, exploring and quantifying how these dimensions interact is crucial. This chapter aims to do so by proposing a methodology to explore, identify, and quantify these influences. The multi-criteria selection methodology, similar to the one used in the first chapter and based on the DANP technique, was employed to determine how policies contribute to both climate action and gender equality. The findings reveal that when gender criteria are considered, the prioritisation of policies shifts significantly, highlighting which policies are most effective in simultaneously reducing cities' carbon footprints and advancing gender equality.

This methodology is not only valuable for understanding the relationship between energy transition and gender but is also adaptable to other social perspectives that should be considered in the planning process. Focusing on gender is particularly relevant, not only because it intersects with other social inequalities but also because gender disparity represents a major challenge in addressing urban injustices. Recognizing the scale of gender inequality highlights the need to address diverse and interconnected social issues for an inclusive energy transition. By applying this approach, policymakers can better understand and address the specific needs of diverse social groups within the broader framework of energy transition. The results show that while gender criteria contribute to closing the gender gap, they may also broaden the impact on decarbonisation. However, including gender criteria alone is insufficient to eliminate bias; thus, multidisciplinary teams must participate in the decision-making process to ensure comprehensive and equitable outcomes. This chapter highlights the importance of integrating social dimensions into technical planning processes, ensuring that the benefits of the energy transition are distributed equitably across all segments of society.

Building on the focus on social inclusion and quantifiable methodologies in the previous chapter, the fourth chapter addresses the challenge of integrating vulnerable households into shared photovoltaic self-consumption systems within REC. Social inclusion is often approached qualitatively in energy transition discussions, but this chapter tackles it through a quantifiable, methodological lens, addressing the practicalities of implementation. This strategy is presented as an effective way to mitigate energy poverty, being more cost-effective for public institutions than traditional energy subsidies. Additionally, it promotes the inclusion of these households in the energy transition and contributes to reducing greenhouse gas emissions.

This study goes beyond identifying the need for social inclusion by exploring the proposed solution's technical, social, economic, and administrative viability.

Technically, not only is this approach viable, but it also promotes the optimal use of available rooftops for energy generation. Socially, the initiative ensures that even the most vulnerable citizens have access to renewable energy, overcoming barriers such as initial investment costs, whether households are rented or owned, and potential digital divides so that the fluidity of families moving in and out of poverty does not prevent them from accessing the energy they need. Economically, the households that benefit from this initiative experience significant savings on their energy bills while being guaranteed energy access. For public institutions, this approach offers greater long-term economic returns compared to providing direct monetary subsidies.

Economically, the households that benefit from this initiative experience significant savings on their energy bills, with the case study showing potential savings increases of up to 82% per household in the most favourable scenario. Furthermore, this approach offers greater long-term economic returns for public institutions than direct monetary subsidies, with annual subsidy costs potentially reduced by as much as 58,000 € . This dual benefit—providing savings for households and reducing public spending—demonstrates the economic efficiency of this model.

By tackling energy poverty through innovative community-based solutions, this chapter demonstrates how targeted interventions can simultaneously address environmental and social goals, fostering a more inclusive energy transition. The quantifiable approach not only offers a structured way to assess the impact of such initiatives but also provides a replicable model that can be adapted to different contexts and scales. Although, in this case, the inclusion in the energy community has been compared with state-level support, with the necessary information on local support, a comparison could be made that would allow municipalities to see the potential of this measure in their interventions to help them tackle fuel poverty. This could have a more significant impact on the implementation of this solution.

These four studies provide a combination of proposals for planning and implementing urban energy transitions that promote sustainability and social justice. Each study builds on the findings and methodologies of the previous ones or adds nuances to the previous ones, creating a cohesive and holistic approach that addresses the diverse challenges of the energy transition in cities. The integrated nature of these studies ensures that technical solutions are informed by social considerations, making the energy transition more inclusive, equitable, and effective in achieving long-term sustainability goals.

Chapter 7

Conclusions and future research

7.1 Conclusions and contributions

This thesis has explored the development of methodologies for planning a fair and sustainable energy transition in urban areas, with a particular focus on both technical and social aspects, aligning with the goals of the Climate-Neutral and Smart Cities Mission. By conducting four interconnected studies, this research provides an integrated and holistic approach to addressing the diverse challenges of the energy transition in cities, using Valencia as a key case study.

The study begins with a comprehensive assessment of the city, prioritising areas or districts for targeted interventions. This approach allows for identifying priority districts, key differentiating factors, and their relevance, forming a strategic framework for the city. Through this process, it becomes clear which districts should be prioritised for transformation into PED and which pose greater challenges due to limiting factors, which can then be strategically addressed. Visualising each district's strengths, limitations, and suitability for PED transformation enables establishing the necessary connections to create a balance in the city. The proposal for evaluation and prioritisation of urban districts using the DANP methodology was studied and applied in Valencia with the participation of the General Coordinator of Urban Strategies and Sustainable Agenda in the Mayor's Office of the City Council of Valencia and with the involvement of various stakeholders from academia and civil service of Valencia. The fact that this study contributed to the proposal presented for València to be declared Mission City reinforces its value for developing a city strategy.

After studying the macro level, the focus shifts to the next level of detail, developing a methodology for energy planning within these districts. This approach proposes a methodology based on studying various scenarios and conducting a sensitivity analysis, allowing the establishment of a common pathway among these scenarios to outline the initial steps in the district's transformation while providing flexibility for adaptation over time. This methodology was applied in La Marina de València, an urban waterfront area within one of the districts identified in the initial macro analysis. The energy planning study of LMDV was carried out with the support of the strategic director of the València 2007 Consortium, the entity then responsible for managing and operating LMDV, along with the LMDV infrastructure service. This study highlighted how UWFs, with their ample spaces and resources, are particularly well-suited for PED development, playing a significant role in urban decarbonisation strategies.

Considering the intersectionality of activities and interests in cities, we analysed how selecting policies or actions changes the type of objectives set and the participatory profiles of decision-making. Gender perspective integration in energy transition policies proved to be advantageous for the transition of cities. The research highlighted that considering gender criteria significantly influences the prioritisation of policy actions, underlining the need for a balance between technical and social elements to ensure that all population segments benefit from the energy transition. Including gender criteria contributes to closing the gender gap while having a greater impact on decarbonisation. However, including gender criteria alone is insufficient to avoid bias; multidisciplinary teams must be involved in decision-making.

Finally, this study explored how RECs can help alleviate energy poverty, offering a specific proposal along with a techno-economic analysis of feasibility and implementation. This investigation sparked interest among entities like València Clima i Energia in extending the study and comparing the RECs with municipal subsidies. The analysis of RECs as a solution to energy poverty provides valuable insights into this approach's economic and social benefits. This targeted intervention addresses an inequality within the energy system that disproportionately impacts women and vulnerable groups. Findings reveal that integrating vulnerable households into shared photovoltaic self-consumption systems is more cost-effective than conventional energy subsidies, promoting social inclusion and reducing greenhouse gas emissions.

These four interconnected studies have demonstrated impact and interest in their application in Valencia, providing a comprehensive and holistic approach to addressing the complex challenges of urban energy transitions. Replicating these studies in other cities could not only foster a deeper understanding of the unique obstacles each urban area faces but also actively support their planning processes and the adaptability of these methodologies to diverse local contexts and needs.

7.2 Future research

Further research could explore how to effectively integrate technological, economic, social, and governance innovations into specific PED projects. By carefully considering the criteria used in this thesis, policymakers can identify the most suitable districts for deploying these innovations. Experimental initiatives could be designed to test these innovations in different districts, fostering the replication and scaling up of successful strategies.

For example, in terms of addressing energy poverty, other solutions can be studied to focus on structural and efficiency measures for vulnerable households. This could include exploring innovative financial mechanisms, policy incentives, and community-based approaches to ensure adequate housing conditions so that households can effectively address the health, emissions, and economic dimensions of the problem.

Additionally, future research can examine how to leverage the potential of areas such as UWFs and their energy surpluses for consumption in nearby residential areas. This could involve both technical and governance aspects, ensuring that the energy produced in these areas is efficiently used and managed to benefit surrounding communities.

Comparative studies between different districts can provide valuable insights into the effectiveness of various energy transition strategies. By comparing districts with similar and differing characteristics, researchers can identify best practices and lessons learned, aiding in the refinement of transition methodologies and the creation of more effective policies.

Establishing long-term monitoring frameworks to evaluate the impacts of implemented energy transition policies on social equity, economic development, and environmental sustainability is also crucial. This ongoing assessment will help identify areas for improvement and ensure that policies remain effective and adaptive to changing conditions.

By addressing these areas, future research can build on the findings of this thesis, contributing to more effective and inclusive urban energy transitions. This research will ultimately support global efforts towards sustainable development, ensuring that urban energy transitions are not only technically robust but also socially equitable and inclusive.

Chapter 8

Publications and developed activities

8.1 Peer reviewed Journals

Corresponding to the main focus and objectives of the thesis.

- Aparisi-Cerdá, I., Ribó-Pérez, D., Cuesta-Fernández, I., Gómez-Navarro, T. Planning positive energy districts in urban water fronts: Approach to La Marina de València, Spain, Energy Conversion and Management, vol. 265, 2022, p. 115795, ISSN 0196-8904.
- Aparisi-Cerdá, I., Ribó-Pérez, D., Gomar-Pascual, J., Pineda-Soler, J., Poveda-Bautista, R., García-Melón, M. Assessing gender and climate objectives interactions in urban decarbonisation policies. Renewable and Sustainable Energy Reviews, vol. 189, Part A, 2024, p. 113927, ISSN 1364-0321.
- Aparisi-Cerdá, I., Ribó-Pérez, D., Gómez-Navarro, T., García-Melón, M., Peris-Blanes, J. Prioritising Positive Energy Districts to achieve carbon neutral cities: Delphi-DANP approach. Renewable and Sustainable Energy Reviews. vol. 203, 2024, p. 114764, ISSN 1364-0321.
- Aparisi-Cerdá, I., Manso Burgos, A., Ribó-Pérez, D., Sommerfeldt, N., Gómez-Navarro, T. Panel or check? Assessing the benefits of integrating families in

fuel poverty to energy communities, Sustainable Energy Technologies and Assessments vol. 71, 2024, p. 103970, ISSN 2213-1388.

Corresponding to collaborations beyond the framework of the thesis:

- Vargas Salgado, C., Aparisi-Cerdá, I., Alfonso Solar, D., Gómez-Navarro, T. Can photovoltaic systems be profitable in urban areas? Analysis of regulation scenarios for four cases in Valencia city (Spain), Solar Energy, vol. 233, 2022, pp. 461–477, ISSN 0038-092X.
- Aparisi-Cerdá, I., Gomar-Pascual, J., Pineda-Soler, J., Ribó-Pérez, D. Perspectiva de género en las políticas climáticas urbanas: hacia ciudades climáticamente neutras e inclusivas, Revista Diecisiete, 10, 2024.
- Hurtado-Pérez, E., Bastida-Molina, P., Aparisi-Cerdá, I., Alfonso-Solar, D., Rodríguez Fernández, A. Multicriteria solar photovoltaic potential evaluation for high educational buildings. Case study of Polytechnic University of Valencia, Spain, Renewable Energy, vol. 227, 2024, p. 120560, ISSN 0960-1481.
- Aparisi-Cerdá, I., Ribó-Pérez, D., García-Melón, M., D'Este, P., Poveda-Bautista, R. Drivers and barriers to the adoption of decentralised Renewable Energy Technologies: a multi-criteria decision analysis, Energy, vol. 305, p. 132264, 2024, ISSN 0360-5442.
- Turci, G., Civiero P., Aparisi-Cerdá, I., Marotta, I., Massa, G. Transition Approaches towards Positive Energy Districts: A Systematic Review, Buildings, vol. 14 (10), p. 3039, 2024, ISSN 2075-5309.

8.2 Research stays

- Università Roma Tre Dipartimento di architettura Roma, Italia 02/04/2024 - 28/06/2024
- KTH Royal Institute of Technology, Department of Energy Technology Stockholm, Sweden 01/06/2023 - 31/08/2023

8.3 Conferences

8.3.1 International Conferences

- Manso Burgos, A., Tortosa Navarro, D., Ribó-Pérez, D., Aparisi-Cerdá, I., Gómez-Navarro, T. Critical Variables in the Economic Performance of Renewable Energy Communities in Mediterranean Cities, 18th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 438–438, 2023.
- Aparisi-Cerdá, I., García-Melón, M., Ribó-Pérez, D., D'Este, P., Poveda-Bautista, R., Guiaro-Gómez, J., Ayón-Gascón, M. Identification and Ranking of Drivers and Barriers to Decentralized Energy Technologies: an Analytic Network Process Approach, 18th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 549–549, 2023.
- Aparisi-Cerdá, I., Manso Burgos, A., Tortosa Navarro, D., Ribó-Pérez, D., Gómez-Navarro, T. Panel or Check? Assessing the Benefits of Integrating Families in Fuel Poverty to Energy Communities, 18th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 73–73, 2023.
- Aparisi-Cerdá, I., Ribó-Pérez, D., García-Melón, M., D'Este, P., Poveda-Bautista, R. Identification and Ranking of Drivers and Barriers to Decentralized Energy Technologies: an Analytic Network Process Approach, 2023 Eu-SPRI Annual Conference. Research with Impact, pp. 344–344, 2023.
- Aparisi-Cerdá, I., Ribó-Pérez, D., Gomar-Pascual, J., Pineda-Soler, J., Poveda-Bautista, R., García-Melón, M. Climate-neutral cities with a gender perspective: assessing the interaction between gender and climate objectives in urban policies, 2023 INGENIO PhD Days. Eu-SPRI Early Career online conference. Addressing old and new social challenges: Knowledge, policies, inclusión, 2023.
- Aparisi-Cerdá, I., Ribó-Pérez, D., Gomar-Pascual, J., Pineda-Soler, J., Poveda-Bautista, R., García-Melón, M. Climate-neutral cities with a gender perspective: assessing the interaction between gender and climate objectives in urban policies, 17th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 397–397, 2022.

- Aparisi-Cerdá, I., Ribó-Pérez, D., Gómez-Navarro, T. Systematic proposal of measures against energy poverty at a district level in a Mediterranean city. Actions on the energy quality of dwellings, 17th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 331–331, 2022.

- García-Lepetit, N., Aparisi-Cerdá, I., Brazzini, T., Montagud-Montalvá, C., Gómez-Navarro, T. Measuring the discomfort of energy vulnerable elderly people. Recommendations for solutions, Sustainable Built Environment 2022. SBE, pp. 1–11, 2022.

- Aparisi-Cerdá, I., Ribó-Pérez, D., Gómez-Navarro, T. Planning Positive Energy Districts in Urban Water Fronts: methodology and approach to La Marina de València, Spain, 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), pp. 1–20, 2021.

- Gómez-Navarro, T., Aparisi-Cerdá, I., Ribó-Pérez, D., García-Melón, M. A Delphi-ANP method for identifying potentially next Carbon Neutral Districts, 31st European Conference on Operational Research (EURO 2021), pp. 5–75, 2021.

8.4 Competitive Research projects

- D'Este, P., García-Melón, M., Impulsores y barreras para el éxito de la transición energética descentralizada: la importance del territorio, los adoptates y la madurez tecnológica (TED2021-132601B-I00), 15/02/2023 - 30/11/2024

- Quintana-Gallardo, A., Parametrización de impactos sociales en vivienda: Análisis de Ciclo de Vida Social (PAID-06-23) 01/01/2024 - 31/12/2024

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