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Companion modelling for energy transition: A participatory approach to design positive energy districts in Mediterranean cities

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ABSTRACT

Climate change poses a significant threat to human well-being, making it imperative to transition from the current polluting energy model to one that aligns with the planet's ecological limits. As highlighted by numerous experts and practitioners, engaging local communities in the planning of urban infrastructure and services is essential for accelerating their deployment and fostering public acceptance. However, implementing participatory processes, especially around technical topics like energy, remains a significant challenge. This underscores the urgent need for practical tools, methods, and strategies that can effectively guide public involvement throughout the various phases of local energy planning, such as in the development of positive energy districts (PEDs).

This research seeks to address this gap by proposing an innovative participatory process designed to enhance public engagement during the modelling phase of PEDs, following the companion modelling approach. The study is structured around three key objectives. First, it establishes a theoretical framework for public participation in PED modelling, identifying good practices and effective methods. Second, it presents a novel methodology, built on existing approaches, for participatory modelling of PEDs in Mediterranean cities. Finally, it introduces a three-session participatory process that immerses stakeholders in the transformation of their district, fostering a deeper understanding and ownership of the proposed changes.

1. Introduction

The transformation of the current contaminating energy model into one that respects the limits of the planet constitutes a central pillar of most climate agenda, from global to local scale [1,2]. In cities, this transformation takes the form of initiatives aimed at improving the efficiency of the building stock and infrastructures, supporting the deployment of decentralized production based on renewable energy sources (RES), and fostering the integration of smart technologies [3–5]. Despite these clear actions and roadmaps, local authorities and decision-makers are facing difficulties to launch and maintain ambitious and efficient strategies that deeply reshape urban energy structures [6].

In this pressing context, experience shows that accelerating the adoption of energy measures can be achieved by actively engaging citizens and local actors who are going to use them or benefit from their implementation [7–9]. To empower users effectively, it is essential to raise their awareness of energy-related challenges, encourage the integration of energy-conscious practices into their daily lives, and enable their active involvement in the energy system [10]. According to Wahlund et al., these active forms of engagement are more likely to emerge at the local scale and within decentralized energy systems, as promoted by initiatives like energy communities and positive energy districts (PEDs) [11]. While PEDs focus on the physical transformation of the district [12], the term energy community is more related to a change

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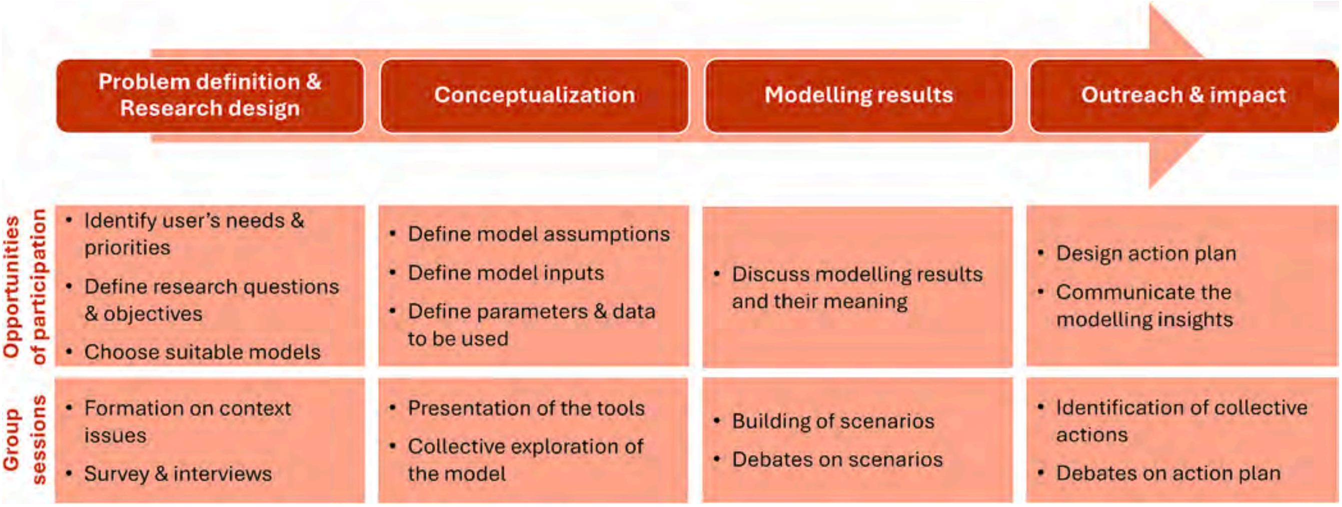


Fig. 1. Opportunities for participation existing among the modelling and simulation process built on the basis of [34–36].

within the governance of the energy system [13]. Several authors suggest that the combination of both concepts could constitute a suitable and powerful approach for the deployment of impactful, inclusive, and participatory energy projects [12,14–16].

Despite this potential, there are currently difficulties to translate concept and intention into successful practical experiences [17,18]. Indeed, the implementation of a participatory process is an arduous task, that becomes even more complex when it comes to technical topics such as energy ones. People use to feel disconnection, vulnerability, and mistrust towards energy, due to a lack of understanding of related technologies and issues [19]. As previous studies and reports have emphasized, these social barriers pose substantial obstacles to the growth and implementation of grassroots energy initiatives, hindering their potential and widespread adoption [20–22]. Although this challenge has been acknowledged, practitioners still lack accessible tools to effectively bridge social dimensions and technical design [23].

Against this backdrop, there is a need for practical approaches and ready-to-use methodologies that support the inclusion of participatory processes in the different phases of local energy planning, from conception to implementation. To address this gap, the present research focuses on integrating quality public participation in the modelling phase of PEDs. First, it aims to define a theorical framework of public participation in PED modelling, leading to the identification of good practices and methods. Then, it describes a novel methodology, built on existing approaches, for the participatory modelling of PEDs in Mediterranean cities. Finally, it introduces the resulting process made of three group sessions that immerse participants in the transformation of their district.

The remainder of this paper is structured as follows to address each of the research objectives. Section 2 presents the theoretical framework of the research, providing an overview of key concepts and existing approaches to participatory energy modelling in general, as well as their application specifically to the field of energy. Then, Section 3 moves to the methodology for the conception of the participatory process, which is presented in Section 4. Finally, these results are discussed in Section 5 and some conclusions are drawn in Section 6.

2. Theorical framework

2.1. Participatory energy modelling

Energy plays a pivotal role within the transition of societies towards sustainability [24]. Therefore, the accurate prediction of the comportment of energy assets to be implemented is essential for the definition of realistic decarbonization roadmaps. In that context, results obtained thanks to software models are usually the baseline used by practitioners to optimize the design and planning of energy systems. Several reviews have been dedicated to the analysis of existing software models focused on energy, to identify their key features and outputs, and outline their pending limitations [25–30]. One of the main challenges outlined within these reviews is to find the right balance between model's complexity and effectiveness [31]. Indeed, the reliability and relevance of energy models' results depend on many parameters that encompass technical, environmental, social, and economic aspects.

According to McGookin et al., the involvement of multidisciplinary teams and of stakeholders in the conception of energy systems through participatory modelling methods could help address this issue [23].

Participatory modelling is defined by Voinov et al. as "the use of modelling in support of a decision-making process that involves stakeholders" [32]. Various implementations of this practice exist, with key variations emerging from differences in: the model's architecture, the design of participatory processes, and how these components interact [33]. The strength of participatory modelling lies in its adaptability - it offers a wide spectrum of stakeholder engagement possibilities. This flexibility allows the approach to be customized according to the specific requirements and context of each decision-making scenario, making it a versatile tool for collaborative problem-solving and decision-making process.

Participatory activities typically occur during group sessions designed to support stakeholders in the building of ideas, concepts, strategies, or plans that benefit them. The involvement of stakeholders may occur at different stages of the process of defining, developing, and using the model [34]. Fig. 1 shows examples of opportunities for participation existing among the modelling and simulation process, translated in terms of group sessions.

It thus appears that the application of participatory modelling throughout energy planning processes - from design to deployment - can yield multiple benefits. Specifically, it can help identify the real needs and pains faced by local stakeholders, improve the accuracy and realism of models, build ownership and enhance the use of selected solutions, and even support the execution of ambitious strategies that rely on collective actions and awareness [36,37].

2.2. Companion modelling approach

Participatory modelling projects employ diverse methods and tools that they articulate within structured workflows. While existing literature provides valuable method classifications [38–40], few frameworks

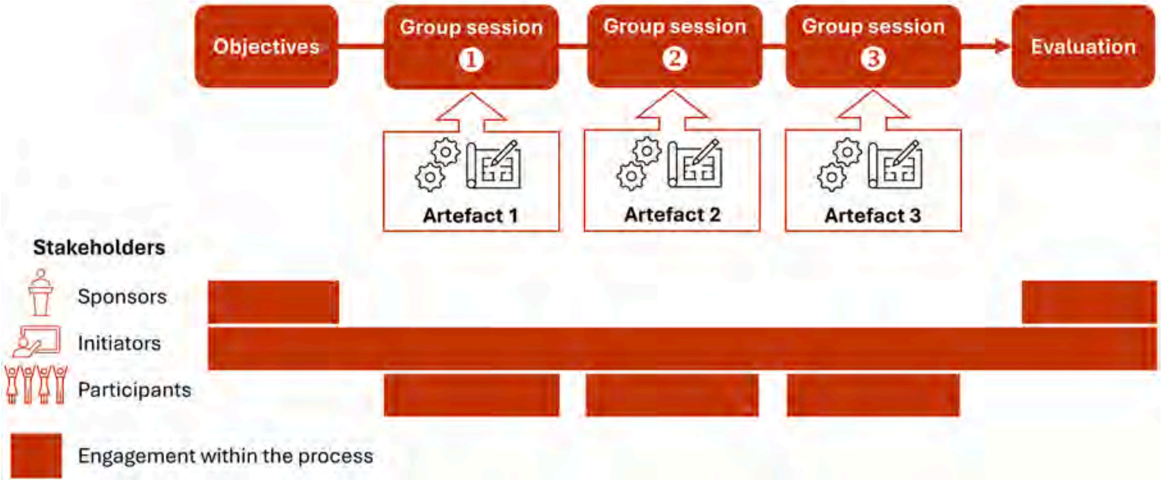


Fig. 2. ComMod's process and main components retrieved from [48].

holistically orchestrate the entire process with embedded toolkits [35]. Soft Systems Methodology and Companion Modelling (ComMod) constitute the two most established approaches for process design [38,41]. The present research falls within the ComMod framework for its superior alignment with co-design objectives and proven efficacy in facilitating multi-stakeholder collaboration [41,42].

ComMod was first introduced in the mid-1990s by an interdisciplinary group of French researchers [43]. This approach is based on a particular vision of participatory modelling practice whose fundamentals and principles have been successively defined and described in position documents [44,45] and scientific papers [46,47].

The fundamental objective of ComMod is to raise the awareness of stakeholders -including scientists and field actors- on the variety of perspectives existing within their context and the consequences that they may have. To do so, ComMod uses modelling to support a collective in a process that will bring him knowledge and exchange of points of views on a specific complex system [47].

The ComMod process, presented on Fig. 2, enables to engage stakeholders in the modelling by means of workshops and artefacts [48].

The workshops are the times in which occur the group sessions, key element of the participatory modelling general framework introduced in Section 2.1. The artefacts are elements -usually concrete objects such as maps, models, or documents- which are intended to represent the reference system and/or support the interactions between the participants. They constitute the link between the different workshops. In that sense, their form may vary, and their content evolve according to the interactions and exchanges occurring during the workshops [34].

Furthermore, the process relies on three types of stakeholders. First, the sponsors which are at the origin of the process. Then, the initiators which design the artefacts, prepare and facilitate the workshops, and coordinate the process. And finally, the participants that take part in the workshops [48].

2.3. Participatory modelling for urban energy planning

Although participatory approaches are increasingly recommended

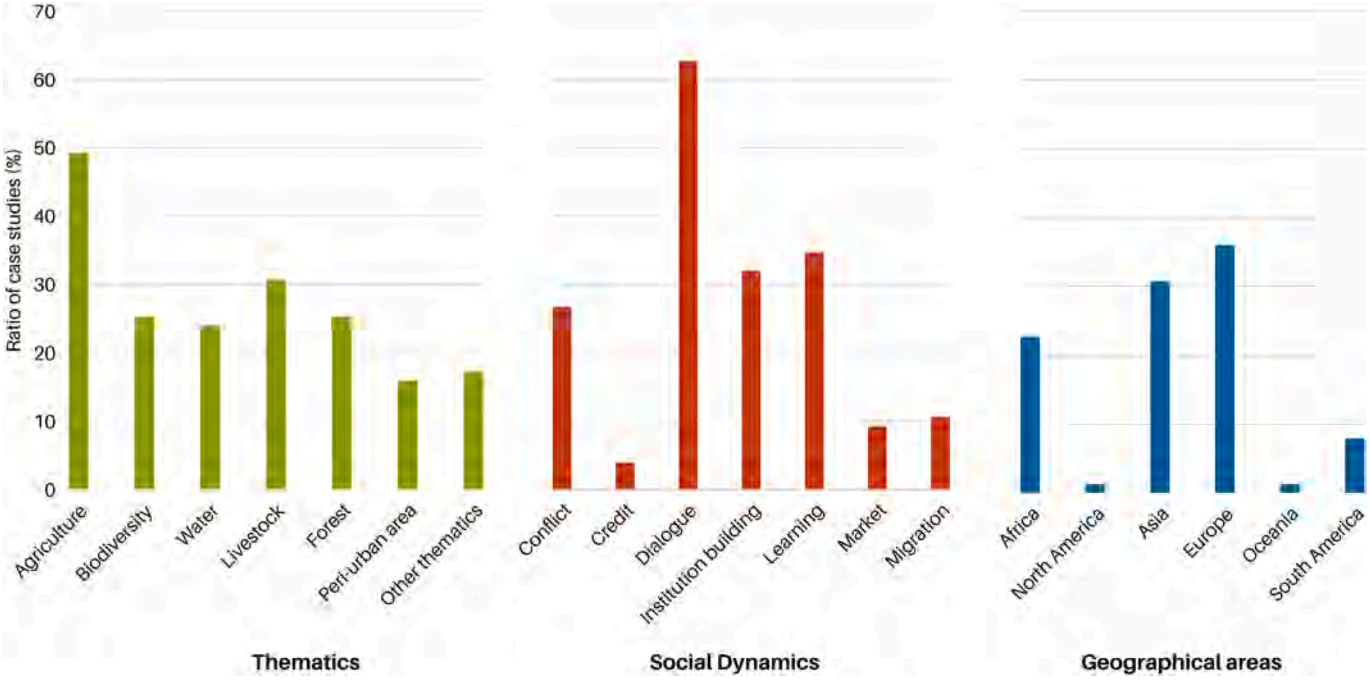


Fig. 3. Distribution of ComMod case studies by thematical focus, type of social dynamics, geographical region.

Table 1
Key Features of ComMod Projects related to energy and local urban development.

Name	Objective	Participants	Artefact and dynamics	Categories	Ref.
TEPOS	Explain the possible stumbling block that can occur during the implementation of an energy project.	Stakeholders involved in the implementation of energy projects.	Serious role-based game that simulates the energy self-sufficiency of a territory.	- Other thematics. - Institution building. - Europe.	[53]
Geranium	Integrate user behaviour aspects into urban renewal programs and explore pathways for improving housing energy efficiency.	Public actors in charge of urban renewal programs.	Computational model for estimating neighbourhood-scale energy consumption under various urban renewal scenarios.	- Other thematics. - Learning. - Europe.	[37]
New district	Improve awareness and foster learning on the impacts of peri-urbanization development on biodiversity.	Executives of construction companies mainly, and to a lesser extent, students and environmental specialists.	Two layers that interact and evolve throughout the simulation: 1) environmental processes simulated by a computer model; 2) social interactions simulated through a stakeholder role-playing game.	- Peri-urban area, Biodiversity. - Institution building, Dialogue, Learning. - Europe.	[54]

for energy systems modelling, systematic reviews demonstrate a significant implementation gap [23,49], with few robust examples in practice [36]. This absence of widespread application has resulted in a lack of established methodological frameworks for designing participatory energy modelling processes. Within this context, this section evaluates the relevance of the ComMod approach—introduced in Section 2.2—for integrating participatory modelling into district-scale energy projects.

ComMod practitioners frame their work and practice as a scientific posture. To advance this approach, they established a dedicated association: The ComMod Network [50]. Its primary objective is to design, analyse, develop, and promote scientific research and applications in the field of ComMod. These resources are compiled and regularly updated on the network's official communication channels and repositories [51]. Drawing from this extensive body of material, a review of ComMod practices has been conducted to characterize the state of the art, identify available resources, and assess limitations—particularly in the context of local urban energy initiatives. Fig. 3 presents an analysis of the seventy-five projects catalogued in the ComMod portfolio [52], assessing their thematic focus, social dynamics, and geographical coverage. Notably, thematic and social dynamics categories are non-exclusive, meaning a single case study may span multiple classifications.

Thematically, most projects centre on natural resource management and activities—such as agriculture, biodiversity, water, livestock, and forestry—primarily in rural settings, with a few extending to peri-urban areas. Social dynamics indicate that these initiatives are principally motivated by three interconnected imperatives: facilitating stakeholder dialogue, advancing comprehension of complex systems and their interactions, and resolving existing or potential conflicts among parties. Geographically, projects are concentrated in Europe, Asia, and Africa.

Furthermore, a comprehensive analysis of the project portfolio enabled the identification of three case studies directly relevant to this research's focus: energy transition at the district level. Table 1 provides a structured overview of these projects, detailing key aspects of the ComMod approach implemented and their respective classification categories.

The analysis reveals three significant patterns in current applications of the ComMod approach. First, projects show an evolution in methodological sophistication, progressing from single-method interventions (TEPOS' role-playing game, Geranium's computational model) to New District's innovative integration of ecological modelling with participatory gaming. Second, stakeholder engagement strategies vary markedly, with New District demonstrating particular strength through its inclusion of diverse sectoral perspectives (construction executives, environmental specialists, and students). Third, a pronounced European focus and predominant reliance on institutional actors - rather than local community participation - highlights a persistent gap in grassroots engagement.

More fundamentally, these cases reveal a concerning narrowness in scope, with each project addressing isolated aspects of energy transition (governance barriers, behavioural retrofits, or biodiversity impacts). This fragmented approach contrasts sharply with the inherently interdisciplinary nature of urban energy transitions, demanding integrated solutions that reconcile the systemic interdependencies linking built environments, public spaces, and socio-technical systems.

To adapt ComMod for district energy planning, substantial improvements are required: develop more holistic modelling scenarios that bridge technical, social and spatial dimensions of transition; incorporate citizen participation, particularly from marginalized communities; and extend testing beyond European borders to validate applicability across diverse urban and governance contexts. Building on the identified gaps in current ComMod experiences, this study proposes an enhanced participatory modelling framework specifically designed to address the multidimensional challenges of urban energy transitions at district scale.

3. Methodology

This section develops a methodology based on the ComMod framework to design participatory processes for local energy projects. It begins by examining the foundational principles of the ComMod approach for participatory process design. These principles inform the subsequent development of a structured methodology for neighbourhood-scale energy planning that systematically incorporates participatory and inclusive practices throughout all phases of project development.

3.1. Companion modelling principles

ComMod distinguishes two level of designs that were first introduced by Klabbers [55]: the Design-In-the-Small (DIS) and the Design-In-the-Large (DIL) [48]. The DIS refers to the conception of the group sessions and artefacts. The DIL relates to the definition and orchestration of the participatory process, made of successive group sessions. The DIS and the DIL require the prior study, analysis, and definition of four constitutive aspects: the intention, the artefact(s), the participants, and the local context [48,56]. These aspects may remain the same all along the process or evolve depending on the group sessions.

3.1.1. Intention

The intention consists in defining the objective of the whole process and of each individual group session. By definition, the purpose of ComMod is to include stakeholders in the decision-making taking place within a system represented by a model. This sharing of the control is done through the modification of the model by participants using artefacts. Among current uses, it is possible to identify three types of intentions: i) to improve communication skills in a complex environment, ii) to increase the comprehension of a system and its dynamics, and iii)

Table 2
Main features of the interactions enabled by the artefact, compiled by authors based on [46,48].

Feature	Design question
Realism and complexity	How the model and the artefact represent the reality?
Decision-making process	How are decisions taken by participants? Which are their effects on the model?
Role asymmetries	Which are the roles available for participants within the simulation?
Ergonomics	How to ensure that the artefact is clear and easy to use by participants?

to share the impacts of different solutions to a given problem [32,48]. It is worth noting that a participatory process may encompass different types of intention at once.

3.1.2. Participants

The selection of the right participants to be involved is another important issue of ComMod design. It consists in identifying the stakeholders and individuals that will give the most valuable contributions to the model, in line with the defined intention. Once selected, the characteristics of participants must be carefully analysed, to ensure that the methods, dynamics, and artefact are in adequation with their capacities and knowledge [57].

3.1.3. Local context

The ComMod approach is aimed at facilitating a decision-making leading to joint action and tangible results. Being embedded in an area that necessarily involves complex and intertwined institutional, political and social dynamics, the success of the initiative also depends on its articulation with the territory. There is consensus in the literature that the correct deployment of a participatory modelling process relies on the prior understanding of the social and institutional local system [46,48,55]. This thorough comprehension relies on the analysis of factors such as the existing mechanisms of governance, the decision-making procedures, or the current regulations and standards, occurring within the territory [56].

3.1.4. Artefact

The artefact that constitutes the interface between the system and the participants can take many different forms depending on the needs and specificities of the process. The role of the artefact is to enhance the understanding of the system, enable participants to perform actions within the model, and generate results based on these interactions. Designing the artefact involves carefully planning and structuring these interactions to ensure they are meaningful and effective. Table 2 outlines the main features that need to be defined to achieve this goal.

3.2. Companion modelling for districts energy planning

3.2.1. Case study: a district in the Mediterranean

In the last few years, there has been an increase interest for initiatives focused on activating energy transition from a bottom-up perspective. Indeed, district, neighbourhood, or community, constitute adequate scales to address complex and multidimensional urban challenges [58]. In response to this new opportunity, methodologies and guidelines have arisen to support practitioners in the outline and implementation of local energy projects. However, these novel instruments mainly look at the energy design from a technical point of view and fail at addressing socio-economic, political, and environmental dimensions [59].

This study aims to address this issue by using ComMod for the planning of PEDs in the Mediterranean region. PEDs are defined as energy efficient urban areas that achieve a positive energy balance on an annual basis and net zero greenhouse gases (GHG) emissions [12]. This concept promotes decentralized planning and management of energy systems, empowering local communities to take control of their energy resources. By reducing reliance on centralized grids, fostering adaptability, and implementing sustainable energy solutions tailored to local needs, PEDs play a crucial role in enhancing urban resilience [60]. This bottom-up strategy appears thus particularly relevant for Mediterranean cities, a cross-continental area facing several multidimensional challenges, such as resource scarcity, climate vulnerability, and socio-economic disparities [61]. The integration of these multifaceted issues into cities' energy transition strategies is essential for advancing sustainability in the Mediterranean region [62].

The proposed approach falls within the methodological framework PlanPED introduced in [59] and conceived to guide the conception of holistic methodologies for PED planning, design, and implementation in cities. One of the main novelties of PlanPED is the articulation of the three workflows presented on Fig. 4, which enables the connection between the technical design and the stakeholder management of the PED. However, and as outlined by authors, PlanPED constitutes a baseline

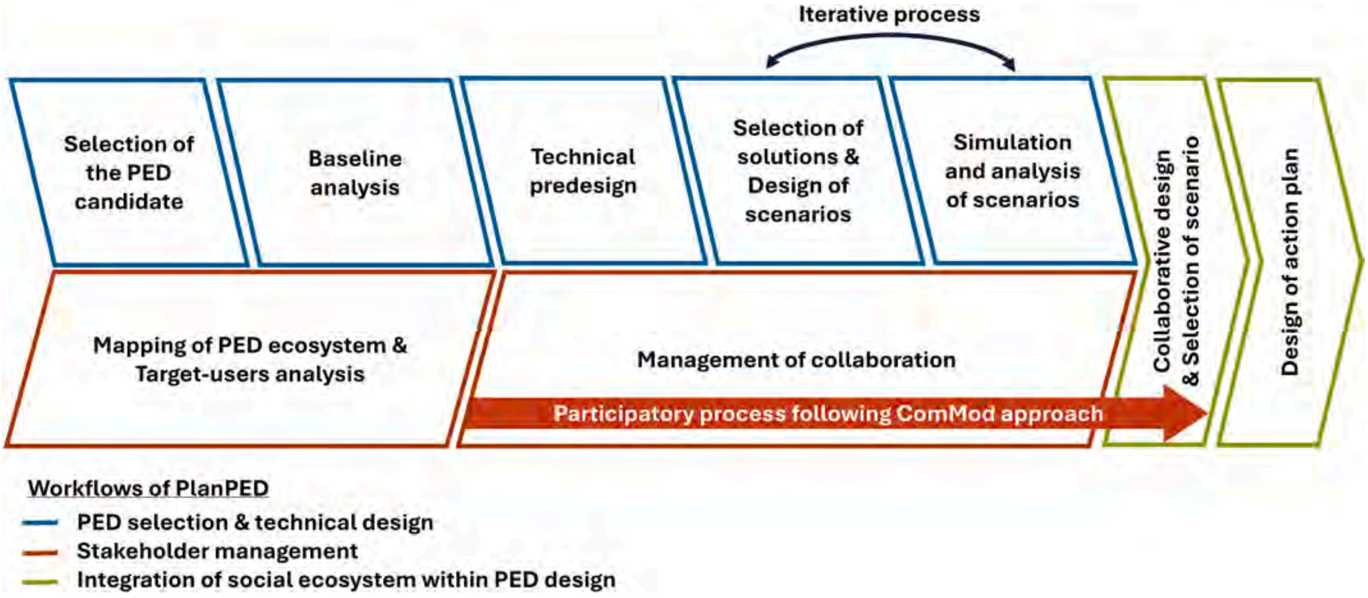


Fig. 4. Inclusion of the participatory process within the workflows of PlanPED, compiled by authors based on [59].

Table 3
KPIs for PED assessment.

Id	Category	Name	Units
EnerP1	Energy Performance	Thermal Energy Consumption	kWh/m^2/year
EnerP2	Energy Performance	Electrical Energy Consumption	kWh/m^2/year
EnerP3	Energy Performance	Thermal Energy Production	kWh/m^2/year
EnerP4	Energy Performance	Electrical Energy Production	kWh/m^2/year
EnerP5	Energy Performance	Self-Sufficiency	%
EnerP6	Energy Performance	Self-Consumption	%
EnviP1	Environmental Performance	GHG emissions Scope 1	kgCO$_2$-eq/year
Envi2	Environmental Performance	GHG emissions Scope 2	kgCO$_2$-eq/year
EnviP3	Environmental Performance	GHG emissions Scope 3	kgCO$_2$-eq/year
EcoP1	Economic Performance	Investment cost	€
SPQ1	Social Performance and Quality of life	Energy poverty	0–1 (Multidimensional Energy Poverty Index scale)
SPQ2	Social Performance and Quality of life	Outdoor thermal comfort	°C (Universal Thermal Climate Index scale)

that needs to be further defined and operationalised depending on local needs and motivations.

In this context, ComMod emerges as an adequate and complementary methodology to guide Mediterranean cities in the effective implementation of PlanPED. Indeed, ComMod could be used within PlanPED framework to connect the energy modelling of the PED with non-technical considerations. This inclusion of ComMod, indicated on the Fig. 4, would thus contribute to articulate the interactions between the different PlanPED's workflows, while taking into consideration the specific requirements of Mediterranean districts.

3.2.2. Adaptation to case study specificities

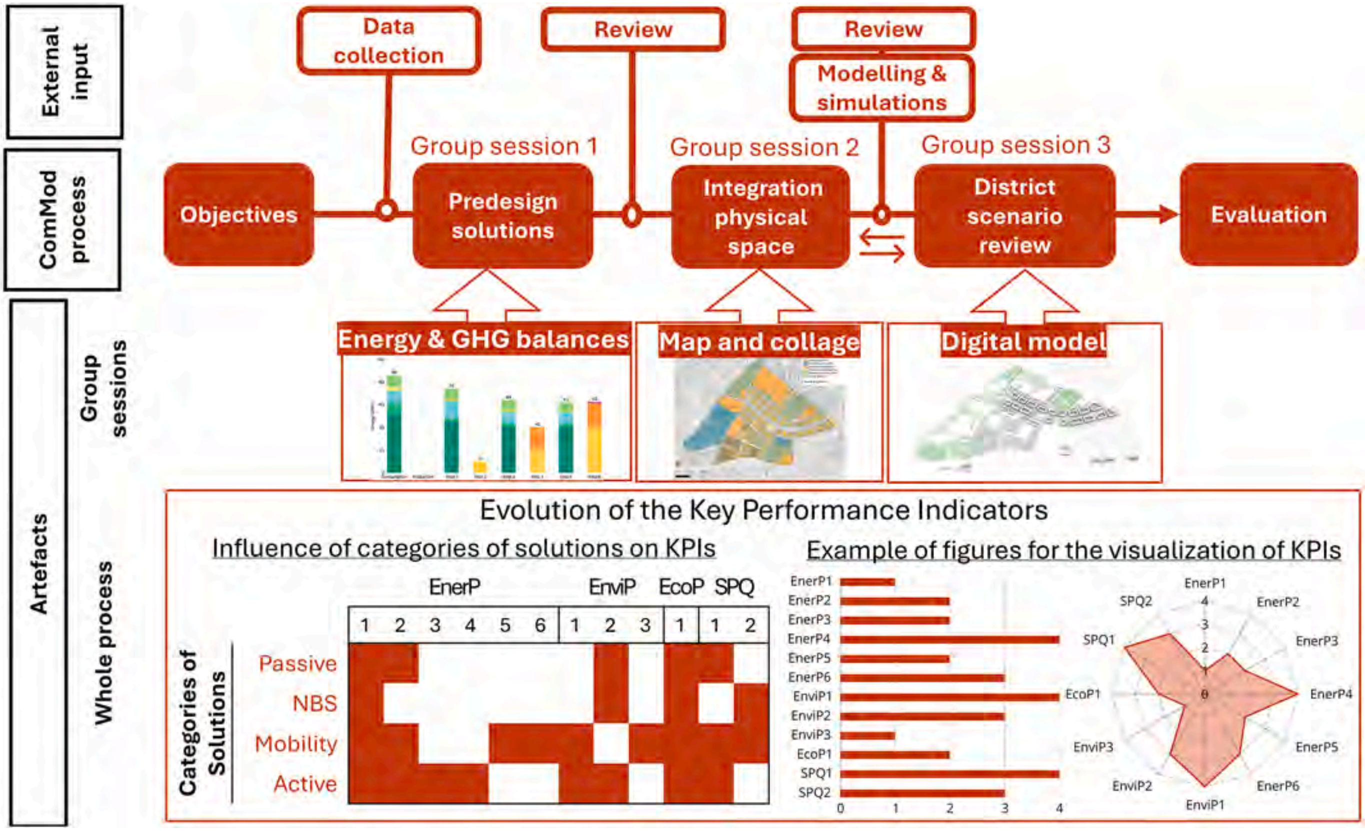
This research follows the ComMod approach to conceive a participatory process that immerses participants in the process of transformation of a neighbourhood into a PED. According to the design principles presented in Section 3.1, it is necessary to begin with the definition of four constitutive aspects, while adhering to PlanPED framework and considering the distinctive features of the Mediterranean context.

First, in respect to the intention, the participatory process is aimed at creating a space of exchange and experimentation in which participants can express their perceptions and preferences. Through the group sessions, participants can identify, select, test, and visualize the impacts that determined actions would have on the energy balance of their district. The assessment of the different scenarios is made by means of the key performance indicators (KPIs) displayed on Table 3. The selection of KPIs and definition of categories have been made following recommendations from reference literature dedicated to PED assessment and evaluation [63–66]. To ensure the holistic approach of the energy planning, a special care has been made to include relevant KPIs related to environmental and social assessment [67].

Following the enounced intention, the artefacts should enable participants to select solutions, include them within the district, and visualize their effects. This process is specifically designed for Mediterranean districts, focusing on solutions that tackle the unique characteristics and harness the opportunities of Mediterranean urban areas. Table 4 presents a preliminary catalogue of solutions tailored for Mediterranean districts. These solutions have been selected from existing catalogues on urban energy transition [68–70], with careful consideration of the Mediterranean context [61,71–75]. Four categories of solutions—applicable to both buildings and their surrounding environments—have been identified as particularly relevant for addressing the specific needs and dynamics of the region.

Table 4
Catalogue of solutions for the energy planning of Mediterranean districts.

	Solutions	Description	Mediterranean context
Passive	Retrofit	Change windows; Insulating; Natural ventilation.	- Changing climate conditions & extreme events. - Heritage preservation & cultural identity. - Vernacular architecture. - Informal settlements & activities. - High population density.
	Efficient appliance	LED lighting; High-performance appliances.	
	Change of habits	Efficient energy use; Responsible living conditions.	
	Pavement & shading	Cool material; Shading systems.	
NBS	Green structure	Green walls and roofs.	- Changing climate conditions & extreme events. - Droughts & water shortages. - Narrow streets & small squares. - Poor air quality & traffic congestion. - Environmental fragility & high biodiversity.
	Landscaping	Reforestation; Renaturalization.	
	Water	Drainage-Bioretention zone; Permeable pavement; Evaporative cooling.	
Mobility	Electric mobility	Charging points.	- Heritage preservation & cultural identity. - Narrow streets & small squares. - Poor air quality & traffic congestion. - Informal settlements & activities. - Marginalized communities & gentrification.
	15 min city	Multi-purpose building/space; Pedestrian areas; Bike infrastructures.	
	Collective transport	Car sharing; Climate ticket.	
Active	HVAC	Aerothermal heating, ventilation, and air conditioning (HVAC); Mechanic ventilation.	- Changing climate conditions & extreme events. - Heritage preservation & cultural identity. - High population density. - Availability of renewable energy resources.
	DHW	Solar-powered domestic hot water (DHW).	
	RES production	Photovoltaic modules. Only district scale: Bioenergy; Wind turbines; Geothermal installations.	
	Local energy use	Energy storage systems; Demand-side management; Vehicle to Grid.	



Categories of Solutions	EnerP						EnviP			EcoP	SPQ	
	1	2	3	4	5	6	1	2	3	1	1	2
Passive	🟥	🟥						🟥		🟥	🟥	
NBS	🟥							🟥		🟥		🟥
Mobility	🟥	🟥			🟥	🟥	🟥		🟥	🟥	🟥	🟥
Active	🟥	🟥	🟥	🟥			🟥	🟥		🟥	🟥	

Fig. 5. Workflow, dynamics and tools of the participatory process, compiled by authors.

Then, according to PlanPED recommendations, the participatory process should prioritize the inclusion of district residents and local stakeholders—those who live in, work in, or regularly visit the area. These individuals are directly affected by and impacts of global and local energy challenges (e.g., contamination, climate change, energy prices, etc.) [36], making their perspectives crucial for envisioning future scenarios [76]. Their lived experiences provide a foundation for accurately diagnosing the current situation and fostering acceptance of proposed solutions.

Equally important is ensuring representation across different social and sectoral groups [11]. For instance, a family facing energy poverty and a local shopkeeper will bring different concerns and values to the process [77]. Recognizing all viewpoints as valid, the process must be designed with inclusivity at its core—from workshop content and format to scheduling and communication strategies [17,18].

Finally, the participatory process takes place within a local context in which the participants interact. This context, which is pre-existing to the implementation of the workshop, can be defined by a set of variables. In the scope of this research, the local context is the district to be converted into a PED. It is worth noting that several actions included in the scenarios, such as mobility measures or energy production, must also acknowledge elements that fall beyond the physical boundaries of the district. In that sense, some characteristics to be considered as part of the local context will also rely on an analysis of its surroundings (e.g. neighbouring areas, wider urban units). According to Daré et al., this analysis should encompass three key dimensions: institutional (e.g., procedures, rules, policies), biophysical (e.g., microclimate, biodiversity, energy flows), and social (e.g., governance mechanisms, attributes of the social ecosystem) [57]. Additionally, these dimensions must be evaluated in light of how the distinct characteristics of the Mediterranean context may shape or influence them.

4. Results

4.1. Process

The participatory PED planning process is organized into three group sessions, each supported by specific tools and methods detailed in Sections 4.2, 4.3, and 4.4. These sessions aim to generate a realistic understanding of the conditions and requirements for implementing solutions in Mediterranean contexts.

According to the ComMod approach (see Fig. 2) the process involves three key roles: participants, a sponsor, and a team of initiators. First, as outlined in PlanPED, the municipality should act as the sponsor of the process, ensuring its legitimacy and conceptual grounding. The initiators —ideally a mix of local and external experts— design artefacts, facilitate sessions, and coordinate the activities. Their expertise spans energy modelling, urban planning, environmental assessment, and

Table 5
The phases of the first group session.

Phase & Name	Duration	Description
0. Data collection	A week	Dual data collection approach: 1) Spatial/urban data (geodataframes of buildings/infrastructure) from datasets, monitoring, and citizen science. 2) Participant questionnaires (energy profiles, GHG emissions Scope 3).
1. Starting situation	0 h30	Comprehensive presentation of district's including: -Current energy flows. -GHG emission profiles.
2. Attempt to balance	2 h	Six-step process to balance energy consumption and RES production across three scales, keeping the alternance between consumption reduction (CR) and RES planning: 1.Housing Unit: -Step 1 (CR): Occupant-focused efficiency measures encompassing technical, behavioural and thermal aspects. -Step 2 (Microgeneration): Distributed energy generation systems and energy management measures. 2. Building: -Step 3 (CR): Integrated efficiency interventions at the whole-building scale, encompassing the building envelope, systems, green structures, and communal areas. -Step 4 (Collective Systems): Shared energy infrastructure for production, storage and management. 3.District: -Step 5 (Urban Optimization): Public realm interventions including bioclimatic design, landscaping, water management and mobility. -Step 6 (District RES): Neighbourhood-scale infrastructure such as RES microgrids, district heating/cooling networks, smart charging hubs.
3. Synthesis and discussions	0 h30	Critical evaluation of integrated scenario impacts, implementation pathways, stakeholder tradeoffs.

community engagement.

Fig. 5 outlines the workflow, which includes the three structured three-hour group sessions, each preceded by a one-week preparatory phase. This interval allows initiators to process inputs, refine materials, and ensure continuity between sessions. The process is supported by a Python-based computational environment that integrates data management, energy modelling, and participatory tools. A centralized spatial database underpins the system, harmonizing technical and social data and enabling spatial-analytical operations through a unified interface.

Two types of artefacts are used: session-specific tools and a shared artefact that tracks KPI evolution (see Table 3). This common artefact illustrates progress towards goals such as positive energy balance, GHG neutrality, and sustainability. Fig. 5 also shows the influence of solution categories on each KPI and presents consistent visualizations to link insights across all sessions.

4.2. Group session 1: Predesign of solutions

The first group session constitutes the initial introduction to the system and its dynamics. In this context, its specific objective is dual: facilitating the preliminary visualization and testing of solutions, while also enhancing participants' knowledge and understanding of the energy systems and infrastructures of their district.

Instead of being designed from scratch, this group session is based on the workshop OGRE (French acronym for “Ordre de GRandeur des Énergies”, in English “Order of Magnitude of Energies”) [78]. OGRE is an activity designed by Grégory Kotnarovsky that invites participants to explore and grasp the orders of magnitude of energy scenarios for the French energy transition. This collaborative serious game follows three successive phases. The initial phase establishes the conceptual framework by explaining the game mechanics, system boundaries, and national energy context, while providing participants with personalized energy consumption profiles derived from pre-workshop questionnaires. The core activity comprises five progressive stages that first engage participants individually before transitioning to team-based collaboration. Participants alternate between identifying consumption reduction measures and planning renewable energy deployment, while respecting budget constraints and progressively increasing ambition levels across stages. The workshop culminates in a comparative analysis phase where teams characterize their scenarios through descriptive titles, present their solutions, and engage in facilitated discussions about intervention effectiveness and alternative transition pathways.

While the OGRE workshop was originally developed for national-scale energy transition analysis in the French context, the current study implements a modified version adapted to local district-scale applications in Mediterranean urban environments. This adaptation preserves the fundamental physics-based energy modelling approach of the original framework while incorporating several critical modifications to address contextual differences across multiple dimensions.

These needed adaptations result in substantive changes to both content and structure while maintaining the original three-phase workshop format. The modified framework introduces district-specific energy profiles, localized solution sets, and place-based constraints that reflect urban rather than national conditions. Table 5 documents these adaptations, describing the district-scale Mediterranean version across the different workshop's phases.

The result of the workshop is a preliminary design of the district which consists of a selection and rough quantification of solutions to implement. This output reflects the collective preferences and priorities of participating stakeholders. The whole list of possibilities of solutions given to participants are described in Table 4 and must comply with basic context restrictions (e.g. available space for solutions, improvement potential of existing urban structure). They thus also depend on the prior analysis of the district.

Concerning the artefact, the session employs a dedicated digital platform that supports distinct functionalities at each phase of the workshop. The platform's architecture follows the “model-view-controller” framework, enabling seamless transitions between data input, processing, and visualization functions [79]. During the preliminary Data Collection phase (Phase 0), the platform enables the cleaning and process of urban information and hosts an integrated questionnaire interface for participant input. Phase 1 features diagnostic dashboards that present the district's baseline energy and GHG emissions metrics through standardized visualizations. The “Attempt to balance” Phase incorporates two key digital tools: a solution selection interface for choosing interventions and dashboards that display energy and GHG emissions balance at each step. Finally, Phase 3 is based on the dashboard resulting from step 6, allowing stakeholders to compare the transition pathway proposed by the different teams. Fig. 6 illustrates this

Name Surname
Team Number

STEP N° 6

PERSONNAL METRICS (/yr):

Energy consumption: 20 kWh
Energy production: 40 kWh
GHG emissions: 19.09 kgCO2eq
Remaining budget: 10.564 €

TEAM METRICS (/yr)

Energy consumption: 62 GWh
Energy production: 63 GWh
GHG emissions: 10 kgCO2eq
Remaining budget: 23.045 €

Score: 9,567

Fig. 6. Platform interface during final scenario comparison. Illustration designed on the basis of OGRE

Table 6
The phases of the second group session.

Phase & Name	Duration	Description
0. Scenario review	A week	Verification of Session 1 outputs by initiators: -Solution selection/quantification validity. -KPI translation accuracy. Outputs: Validated scenario. Ensures evidence-based foundations for Session 2.
1. Introduction	0 h30	Presentation of: -Refined scenario (post-review). -Session protocol: stages, boundaries, deliverables. -Conflict-resolution framework.
2. Creative mapping	1 h 30	Small-group activity: -Collaborative solution mapping on scaled district plans. -Physical tokens represent interventions (aligned with quantified solutions). -Digital visualization tools support precision.
3. Scenario Debate	1 h	Structured presentations/discussions: -Group proposals + identified spatial conflicts. -Resident-led case study on local space-use challenges. -Facilitated plenary to resolve pending issues.

platform interface during final scenario comparison, demonstrating how these technical components integrate into a cohesive decision-support tool.

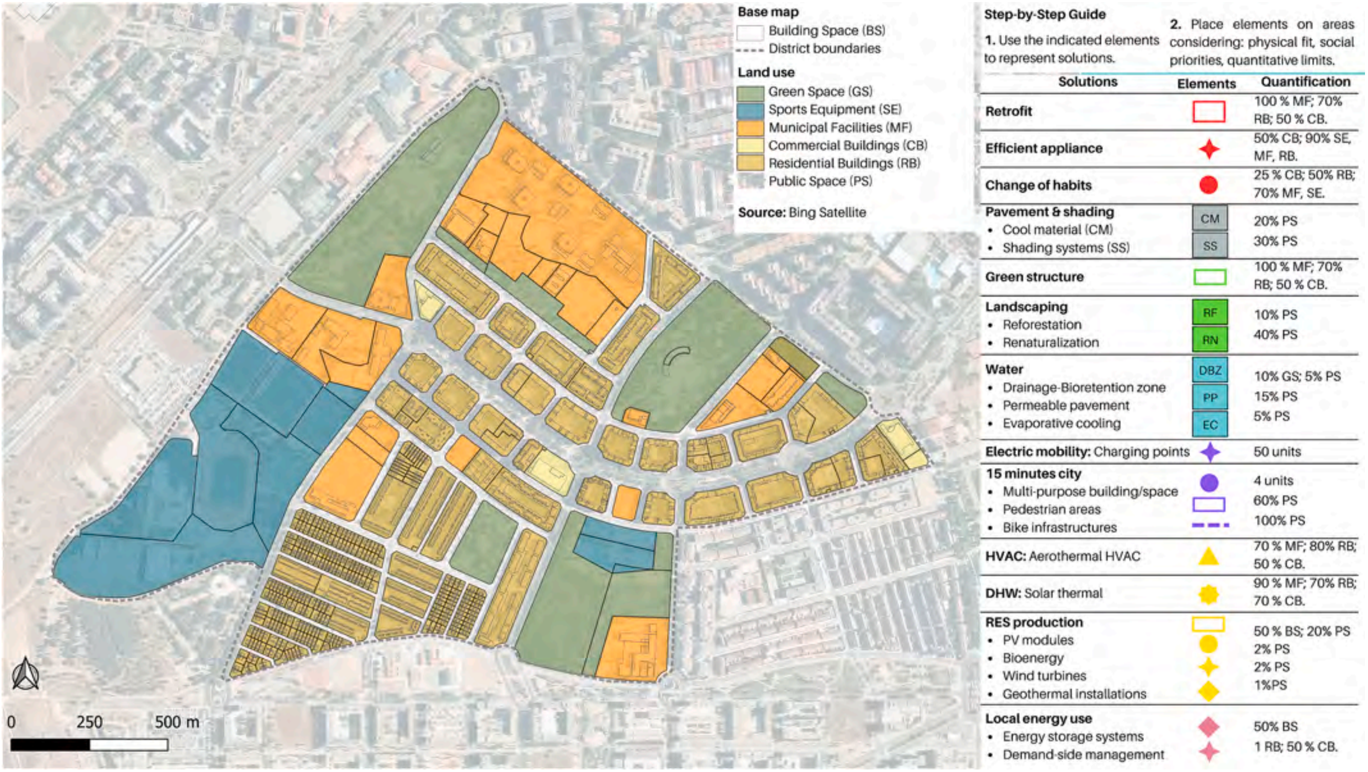
4.3. Group session 2: Integration within the physical space

The second participatory session focuses on the spatial integration of selected energy transition solutions within the district's urban fabric. Using a physical-digital approach, participants collaboratively locate and configure solutions across different scales, from individual buildings to public spaces. Table 6 describes the phases and timeline of the session.

The session employs a hybrid artefact to facilitate participatory spatial planning of energy transition solutions. As illustrated in Fig. 7 through a case study in Alcorcón, Spain, the physical component consists of 1:1000 scale printed district maps showing current land uses and building functions, accompanied by tangible modelling elements representing the different solutions. Critically, the number of available physical elements corresponds to the rough quantification of solutions (indicated as “Quantification” in the map legend) determined in the first workshop, ensuring consistency with prior decision-making. This physical toolkit is enhanced by complementary digital visualization tools that provide additional layers of information (e.g. orthophotos, 3D building models, and street-level views).

This spatial integration process intentionally surfaces and navigates conflicts through structured deliberation. As participants collaboratively position solutions across the district map, divergent perspectives emerge regarding optimal intervention locations, particularly when addressing competing land uses or shared infrastructure. These discussions reveal underlying tensions between stakeholders, such as residents prioritizing green spaces versus technicians emphasizing energy infrastructure. Following the ComMod approach [80], initiators employ non-directive mediation techniques to transform conflicts into learning opportunities. Rather than prescribing solutions, they guide participants to collectively analyse trade-offs between competing priorities while considering measurable criteria like energy yield versus social benefit. This workshop generates several key outcomes: suitable areas for implementing solutions, existing barriers and opportunities related to space, hybrid solutions that creatively reconcile different viewpoints, documented conflict resolutions that inform implementation, and shared understanding of system interdependencies among stakeholders. The tangible outputs - including annotated maps, configuration records, and conflict resolution documents - serve as critical references throughout subsequent project phases while maintaining the participatory legitimacy established during the co-design process.

The approach proves particularly valuable in Mediterranean urban contexts, where high-density development and competing demands for limited space require careful negotiation. By surfacing conflicts early in the planning process, the methodology helps build consensus while



Step-by-Step Guide

1. Use the indicated elements to represent solutions.

2. Place elements on areas considering: physical fit, social priorities, quantitative limits.

Solutions	Elements	Quantification
Retrofit	▭	100 % MF; 70% RB; 50 % CB.
Efficient appliance	✦	50% CB; 90% SE, MF, RB.
Change of habits	●	25 % CB; 50% RB; 70% MF, SE.
Pavement & shading • Cool material (CM) • Shading systems (SS)	CM SS	20% PS 30% PS
Green structure	▭	100 % MF; 70% RB; 50 % CB.
Landscaping • Reforestation • Renaturalization	RF RN	10% PS 40% PS
Water • Drainage-Bioretention zone • Permeable pavement • Evaporative cooling	DBZ PP EC	10% GS; 5% PS 15% PS 5% PS
Electric mobility: Charging points	✦	50 units
15 minutes city • Multi-purpose building/space • Pedestrian areas • Bike infrastructures	● ▭ - - -	4 units 60% PS 100% PS
HVAC: Aerothermal HVAC	▲	70 % MF; 80% RB; 50 % CB.
DHW: Solar thermal	✹	90 % MF; 70% RB; 70 % CB.
RES production • PV modules • Bioenergy • Wind turbines • Geothermal installations	▭ ● ✦ ◆	50 % BS; 20% PS 2% PS 2% PS 1%PS
Local energy use • Energy storage systems • Demand-side management	◆ ✦	50% BS 1 RB; 50 % CB.

Fig. 7. Map of a district located in Alcorcón, Spain, outlining the current uses of building and public spaces, along with instructions and tangible modelling elements.

Table 7
The phases of the third group session.

Phase & Name	Duration	Description
0. Scenario modelling	A week	Initiators process Session 2 outputs to develop feasible scenarios accounting for: • Regulatory constraints (heritage, urban codes). • Technical limits (grid capacity, structural loads). • Stakeholder priorities from Session 2. Outputs: Modelled scenarios with KPI projections (energy, emissions, cost).
1. Introduction	0 h30	Presentation of: • How Session 2 inputs were integrated. • Constraints encountered. • Finalized scenarios (3–4 options).
2. Scenario Feedback	1 h30	Small-group discussions at thematic tables: • Guided by structured questions encompassing: Personal Impact & Livability, Visual & Sensory Perceptions, Safety & Accessibility, Trust & Process. • Responses captured via post-its/digital tools. • Domain experts rotate to clarify technical aspects.
Break	0 h15	Consolidation of feedback. Initiators synthesize key points.
3. Consensus Building	0 h45	Plenary discussion to: • Present synthesized feedback. • Identify alignment/divergence. • Agree on preferred scenario or need for iteration.

maintaining the technical rigor needed for effective energy transition strategies. The tangible nature of the physical modelling exercise creates an accessible space for these complex discussions, enabling participants with diverse backgrounds to meaningfully engage with both the technical and social dimensions of urban energy planning.

4.4. *Group session 3: District scenario review*

The third group session shifts from hands-on design to structured deliberation, focusing on evaluating modelled scenarios for the district. Unlike previous workshops that emphasized co-creation, this session prioritizes critical discussion of trade-offs, feasibility, and collective preferences. Table 7 describes the phases and timeline of the session.

The workshop utilizes energy modelling software's visualization capabilities to support scenario evaluation across the different phases. During the phase 1, the software's projection mode displays comparative scenario layouts and performance metrics on a large screen, enabling all participants to simultaneously examine district-wide interventions and their aggregated impacts. For small group work (phase 2), the same software is accessed via tablets, allowing participants to interactively explore scenarios through layer toggling and localized zooming. Specific visualization styles may vary depending on the chosen energy modelling software. Fig. 8 illustrates this through the Alcorcón case study, presenting two integrated analysis scales: (1) a district-wide 3D model developed in Rhino displaying building morphology and proposed interventions, and (2) a detailed energy simulation of a representative building performed using Ladybug Tools in Grasshopper. This approach ensures technical rigor while adapting to different discussion needs - from high-level comparative analysis during plenaries to detailed, location-specific examination in breakout groups.

If, by the end of the session, there are too many suggestions or strong disagreements among participants with the proposed scenarios, it may necessitate repeating group sessions 2 and 3. This iterative process continues until a form of consensus or adoption is achieved.

5. Discussion

Through the different sections of the paper were presented the fundamentals and the conceptual structure of a participatory process that enables the inclusion of inhabitants' perceptions and preferences within the energy planning of their district. The present section seeks to recapitulate the key contributions of this research and discuss the aspects to be further defined. This outline of remaining issues serves to introduce important areas for future work.

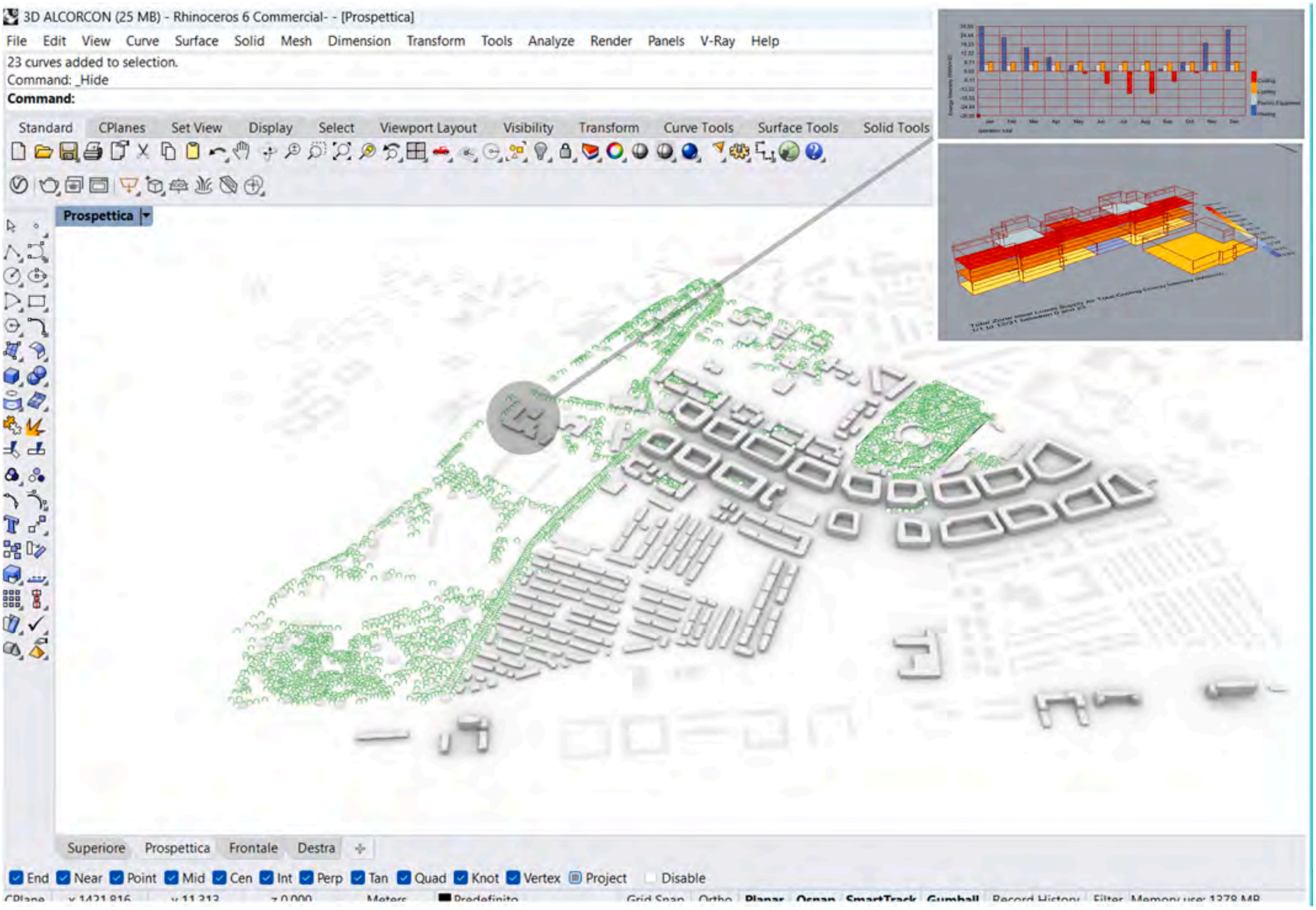


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Fig. 8. Integrated Visualization of the Alcorcón district model: 3D urban morphology with interventions (Rhino), Building energy simulation results (Ladybug/Grasshopper).

5.1. *Application of CornMod to urban energy planning*

This study investigates the application of ComMod to the participatory energy planning of a district. The choice of ComMod was based not only on its proven methodological framework for stakeholder engagement but also on its demonstrated practical effectiveness across various contexts. However, significant complexities emerge when transferring this approach to urban energy transitions. Indeed, while ComMod has been extensively applied to rural resource management, its adaptation to urban energy systems requires substantial adaptations to address technical energy design and urban planning parameters. The tool selection dilemma—identified as a critical open question in ComMod exercises [31] - exemplifies these difficulties. While technical models must meet accuracy and granularity standards for energy solutions [59], participatory contexts transform tools into social artefacts requiring accessibility, ergonomic design, and collaborative functionality [57]. Neglecting these dual requirements in the selection of the modelling tool for group session 3 risks compromising workshop outcomes regardless of technical sophistication.

Prior ComMod experiences (Table 1) nevertheless confirm ComMod's potential to bridge technical and social dimensions in PED design. This suggests that while specific adaptations are necessary, core principles of co-learning and iterative scenario development retain utility in urban and energy contexts.

Future research should address these gaps through the development of a participatory tool taxonomy evaluating available models across technical and social dimensions. These advances would position models as boundary objects mediating between precision and co-creation—a paradigm shift demanding collaboration across modelling, human-computer interaction, and participatory design communities.

5.2. *Rooting for PED implementation*

The resulting practical methodology enables the inclusion of participatory approaches in local energy planning, demonstrating how structured activities can effectively channel community perspectives into district design. Following Ulrich's view that power imbalances can lead to domination in discussions and reinforce inequalities [81], this study deliberately limits initial participation to district residents and local workers. This methodological choice establishes protected deliberative spaces that prioritize grassroots perspectives. However, this approach consequently excludes influential technical, commercial, and regulatory stakeholders (e.g., construction firms, utilities, permitting agencies) whose engagement proves critical for real-world implementation [82]. Unaddressed, this representational gap risks producing plans misaligned with operational complexities—particularly during PlanPED's execution stages where technical negotiations and financing mechanisms determine project viability (see Fig. 4).

To bridge the implementation gap between grassroots visioning and effective execution, future applications should adopt a cascading stakeholder engagement model [83]. This phased approach maintains methodological consistency across the PlanPED workflow while gradually increasing the complexity of stakeholder engagement: initial community-centred activities systematically expand to integrate technical and institutional stakeholders through purpose-adapted ComMod mechanisms. This may facilitate socio-technical negotiations that translate participatory outputs into contractual frameworks (e.g., embedding community benefit clauses in procurement documents). Such transitional protocols are essential for converting co-designed scenarios into implemented realities, particularly for Mediterranean contexts where fragmented governance exacerbates implementation gaps.

5.3. *Tailoring of the process to Mediterranean district*

A central contribution of this research lies in developing a replicable Mediterranean framework that strikes a balance between overly generic and overly specific PED planning approaches [59]. By drawing on shared regional characteristics, the study introduces standardized participatory phases [74]. This approach addresses a persistent methodological challenge: how to reconcile transferability with contextual relevance.

However, according to Gonçalo et al., this focus on shared regional traits should not lead to underestimating critical sub-regional heterogeneities [72]. This tension reveals a fundamental methodological limitation: framing the Mediterranean as a single category can risk oversimplification, potentially masking the nuanced socio-technical configurations present at local levels. Without clear mechanisms for addressing intra-regional diversity, the framework may produce solutions that are misaligned with specific local realities.

This challenge resonates with Jayaweera et al.'s argument that understanding the relations between local socio-technical configurations and the diversity of potential transition pathways remains essential [84]. Consequently, future refinements must integrate contextual calibration protocols that dynamically adapt participatory mechanisms to local power structures and literacy competencies [85]. In doing so, Mediterranean commonalities can serve as a flexible starting point rather than a rigid template, centring contextual diversity as a core design imperative.

6. Conclusions

The aim of this contribution was to present a process designed to engage residents in the energy planning of their district. It begins by outlining the theoretical framework of participatory energy modelling, introducing key concepts and the ComMod approach. The paper then details a methodology for designing participatory processes, specifically tailored to the characteristics of Mediterranean cities. The methodology results from the application of the ComMod approach to the field of energy and urban contexts and is embedded within PlanPED, an existing framework for PED design.

Building on this methodology, a novel participatory process is introduced to promote inclusive and effective urban energy planning. The process is structured around a series of activities and dynamics, organized into three group sessions. These sessions are designed to show citizens and workers the potential actions and solutions that could be implemented in their district, as well as the corresponding impact of these measures on energy balance and GHG emissions. By doing so, it seeks to empower inhabitants, convert them into active actors of the transformation of their neighbourhood, and enhance their energy culture and citizenship.

The methodology has been applied to a reference case study of a Mediterranean city, whose characteristics enabled to set the main structure and phases of the participatory process. As suggested in the discussion, future work will be dedicated to the further definition of the process and the development of the artefacts. Furthermore, ComMod has the potential to support other phases of PlanPED's workflows, offering tailored and practical roadmaps for stakeholder engagement throughout the PED design. By enabling the creation of customized and actionable participatory processes, this approach could play a crucial role in advancing the deployment of PEDs in Mediterranean cities, aligning with the broader objectives of PlanPED.

Finally, this work focuses on a region facing a range of complex issues in achieving sustainable and energy transitions due to its climatic, economic, and cultural contexts. The Mediterranean's geographical positioning—spanning Europe, Africa, and Asia—adds a unique layer of complexity and opportunity, as it brings together diverse governance systems, development levels, and socio-technical conditions. This contribution aims to support Mediterranean cities in tackling these complex issues through the conception of inclusive and participatory urban strategies, ensuring that diverse voices and perspectives are integrated into the planning process. However, the development of tailored solutions must go hand in hand with the strengthening of Mediterranean energy cooperation, which facilitates the sharing of strategies, efforts, and experiences, as well as the deployment of energy infrastructure [86]. Such collaboration is essential to create a cohesive and effective framework for addressing the region's unique challenges and advancing its sustainable energy goals.

CRediT authorship contribution statement

Louise-Nour Sassenou: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Lorenzo Olivieri:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Grégory Kotnarovsky:** Validation, Methodology, Formal analysis, Data curation. **Danila Longo:** Investigation, Formal analysis, Conceptualization. **Francesca Olivieri:** Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition.

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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