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A multi-criteria decision analysis

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Drivers and barriers to the adoption of decentralised renewable energy technologies: A multi-criteria decision analysis

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ABSTRACT

This study explores the complexities surrounding the adoption of decentralised Renewable Energy Technologies in Spain, crucial for transitioning towards a renewable energy-driven economy. Through a systematic review of both scientific and grey literature, key factors influencing adoption were identified. Utilising the Analytic Network Process method, this research highlights political will, technological maturity, and fiscal incentives as primary drivers. These findings underscore the importance of mature technologies and incentivisation strategies in expediting adoption. Conversely, addressing barriers necessitates a multifaceted approach, presenting challenges for policy formulation. However, the analysis reveals a positive cascade effect, wherein strengthening primary drivers positively impacts others within their domain. This pattern is mirrored in the barriers. Furthermore, the study reveals consistent factors across technologies, adopter types, and regions. The three-axis analysis shows the largest differences in terms of the type of adopter, followed by the type of technology. The smallest differences are found by region, emphasising the unifying influence of the EU framework. This suggests a unified approach to policy design and promotion efforts.

1. Introduction

The energy transition involves adopting renewable energy sources (RES) to mitigate climate change. This adoption presents both opportunities and obstacles. While renewable energy technologies imply emission reduction to try to achieve the 1.5 °C objective [1], the energy transition requires structural changes in energy systems. A primary aim is establishing an economy propelled by RES for electricity generation, which will become the primary vector for energy consumption. This multifaceted and profound transition introduces technical, economic, social, and regulatory challenges.

The energy system is experiencing a significant transformation, shifting from fossil fuel-based electricity generation characterised by dispatchability and marginal costs to a focus on RES. These sources, being non-dispatchable and weather-dependent, involve zero marginal costs. Storage and flexibility technologies are imperative as an energy buffer to manage the intermittent nature of RES. Unlike fossil technologies favouring a centralised infrastructure, renewables allow for decentralised deployment. Moreover, due to the variability of renewable generation, consumers will need to adapt and utilise energy when available.

As with any structural transformation, winners and losers emerge. In this evolving landscape, the energy transition towards adopting RES encounters both Drivers and Barriers (DBs). Scholarly analysis of DBs often centres on holistically transitioning to RES, encompassing the replacement of centralised fossil-generating units by large-scale centralised RES schemes [2]. Drivers pertain to climate protection, economic cost reductions, and energy dependency reductions, among others [3]. At the same time, barriers involve regulatory constraints like administrative complexities, economic restrictions such as lack of subsidies, technical challenges linked to insufficient investment in R&D, and societal factors often related to a lack of public awareness. However, when scrutinising decentralised Renewable Energy Technologies (RET), DBs necessitate a context-specific approach [4]. Decentralised energy systems imply a change in power systems' operational, commercial, and regulatory dynamics. These changes bring with them new DBs to the adoption of decentralised RETs.

Decentralised renewable energy systems are gaining prominence. Since 2010, there has been an approximately 100% increase in the number of countries adopting distributed generation policies [5]. Decentralised systems offer several advantages over centralised ones: they

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Nomenclature

$A	Direct-relation matrix
$$a_{ij}$	Values of the direct-relationships matrix
CI	Consistency index
CR	Consistency ratio
RCI	Random consistency index
w_i	weighting of the element (i)
λ_{max}	The largest eigenvalue of matrix A
Abbreviations	
ANP	Analytic Network Process
BE	Economic Barrier
BI	Institutional Barrier
BS	Social Barrier
DB	Drivers and Barriers
DE	Economic Driver
DI	Institutional Driver
DS	Social Driver
DT	Technological Driver
EM	Energy Management
ICT	Information and Communication Technologies
MCDM	Multi Criteria Decision Making
PV	Photovoltaic
RES	Renewable Energy Sources
RET	Renewable Energy Technologies
SLR	Systematic Literature Review

promote energy autonomy, reduce reliance on centralised infrastructure, enhance resilience to natural disasters, benefit local communities by improving energy access, and foster local economies [5]. These advantages have led to staunch support for RET at international [6], national, and regional levels. However, the implementation of decentralised RET is context-dependent.

Firstly, differing technology readiness levels mean that not all technologies face the same drivers and barriers regarding adoption [3]. For instance, while solar Photovoltaic (PV) technology significantly enhances cost competitiveness [7] and enjoys wide social acceptance, storage systems still lack cost competitiveness [8], and changes in energy consumption and flexibility patterns are not universally understood or accepted [9,10]. Secondly, the nature of the stakeholder plays a crucial role. The motivation, willingness, and expected benefits of technology adoption can vary depending on the adopter type. Energy usage and cost might have an influence on the adoption decisions by residential [11] and commercial adopters [12]. Decision-making for an industrial consumer, where energy cost significantly impacts production, may differ from that of a residential consumer, where decisions hold distinct implications. Finally, unlike centralised systems, decentralised systems require more competencies from local actors, and regulations may vary depending on the geographical context. The literature on decentralised RETs tends to focus on a specific technology [13] or sector [14], but a holistic analysis will highlight the main barriers and drivers to their adoption.

Drawing on the discussion in the preceding paragraphs, the following research questions can be inferred:

- RQ1. What are the most relevant Drivers and Barriers influencing the adoption of decentralised RET?
- RQ2. Do these Drivers and Barriers vary based on the specific type of technology and adopter?
- RQ3. Do these Drivers and Barriers vary based on the specific geographical context?

To answer these research questions, an approach grounded in the Analytic Network Process (ANP) is proposed to define and evaluate the importance of DBs. The network elements (DBs) are obtained from a systematic literature review and are further assessed by experts. The method identifies and prioritises critical elements for adopting RET and provides an individual influence index for each network element.

With this analysis, the importance of drivers and barriers to the adoption of RET is evaluated under a two-axis perspective: type of adopter (Industrial and Residential) and type of technology (Batteries, Energy Management (EM) devices and Solar PV). Also, the aim is to understand the existing differences (or lack thereof) among the main elements to provide recommendations for enabling faster and fairer deployment of RET. The study is applied to the case of Spain. While the country's commitment to renewables is in line with the broader objectives of the European Union, responsibility for the implementation of renewable energy policies in Spain is granted to the autonomous communities (Spanish regions). Thus, it is important to keep a regional perspective to fully assess the drivers and barriers to adopting RETs.

The consistency of results across the Spanish regions suggests that while regional differences may exist, they are not pivotal in the broader EU context. Conversely, variations in adopters and technologies are slightly more significant. This implies that while specific details and values may not directly translate to other European countries, general trends and overarching patterns can be extrapolated. However, it is essential to acknowledge the limitations of extrapolating specific values and scenarios from the Spanish case. Context-specific factors, such as regulatory intricacies and stakeholder perspectives, may vary among EU member states, limiting the direct applicability of certain findings. Nonetheless, assuming that general trends can be extrapolated, the study offers valuable insights into the overarching drivers and barriers shaping the renewable energy landscape within the EU.

2. Identification of drivers and barriers

When examining decentralised RET, the assessment of DBs needs a context-specific and adapted approach [4]. Decentralised RET refers to elements that generate, store, or manage electricity at the distribution system level, unlike centralised technologies operating at the transport level. For example, components like rooftop Solar PV, consumer Batteries, and Energy Management software work behind the consumer meter. Existing literature on DBs commonly focuses on renewable energies, in general, [15]. Concerning decentralised systems, the literature often delves into specific sectors, such as the mining industry [14], the water industry [16], or small and medium-sized enterprises [17], or a particular technology, such as battery storage [13], or energy efficiency and demand response [9]. While there is literature on DBs of solar self-consumption business models [18], and adoption [19], and energy communities business models [20] and benefits [21], a comparative analysis of barriers and drivers for different technologies remains unestablished. Likewise, there is a lack of emphasis on the importance of these DBs or their correlation as a problem-solution analysis.

The study employs a comprehensive approach to identify drivers and barriers to RET to address this gap. The method integrates a Systematic Literature Review (SLR) and a review of grey literature. The SLR, a well-established research method, organises and evaluates existing literature on the subject, mitigating research biases and defining a precise review scope [22]. However, it is crucial to note that SLR may not fully capture the'state of the practice' in certain areas, as it typically excludes grey literature [23]. Incorporating grey literature in the review ensures a more holistic understanding of the current landscape, capturing diverse perspectives and insights that may be overlooked in traditional literature reviews.

Table 1
Set of drivers.

Id.	Economic drivers	References
DE1	Fiscal and economic incentives.	[14,27–34]
DE2	Access to sufficient funding.	[14,19,20,24,35]
DE3	Environmental charges.	[36]
DE4	Stabilisation of low energy prices.	[14,21,37]
	Institutional drivers	
DI1	Transposition of European directives.	[9,13,21,30,37,38]
DI2	Political will.	[21,25,37]
DI3	Market participation mechanisms.	[9,13,14,16,18,24,29,35,39]
	Social drivers	
DS1	Clear, reliable and accessible information.	[9,19,20,27,31,39]
DS2	Awareness, education and training programmes.	[20,31,34,37,38,40]
DS3	Adopter's motivation.	[9,21,25,30,41]
DS4	Community culture.	[19,21]
	Technical drivers	
DT1	Existing infrastructure.	[37]
DT2	Technological maturity.	[36,42]
DT3	Development of infrastructures and uses.	[36]

Table 2
Set of barriers.

Id.	Economic barriers	References
BE1	Investment cost (CAPEX).	[9,13,14,18,20,30,32,35,36,39–42]
BE2	Electricity tariff structure.	[14,16,18,43]
BE3	Economic profitability.	[13–15,18,30,37]
	Institutional barriers	
BI1	Lack of technical definition and standardisation.	[14,18,27,35–37,42]
BI2	Institutional inertia.	[13,31]
BI3	Licensing.	[13,30,31]
	Social barriers	
BS1	Risk aversion.	[30,41,42]
BS2	Rejection of dependence on third parties.	[25]
BS3	Lack of energy awareness.	[17,25]
BS4	Lack of know-how.	[14,37,42]
	Technical barriers	
BT1	Space issues.	[9,19,27,37,39]
BT2	Techno-economic uncertainty.	[36,44]
BT3	Technological complexity.	[31,38]

2.1. Systematic literature review

We conducted a systematic literature review using the Scopus database. The final set includes 47 journal publications for the full reading step of the SLR. Additional information on the SLR process can be found in Supplementary material. The literature focuses on identifying barriers and/or drivers for a specific technology (26 of the journal publications), for example, battery storage [13], or specific sectors such as the mining industry [14] or hotel sector [24]. Only six papers included both drivers and barriers and were not focused on specific technologies or sectors. Three of them were focused on centralised systems. The rest focused on the social acceptance perspective [25], business models innovation [18], and dynamics of political power [26] of decentralised systems.

From the review of each journal publication, the identified DBs were extracted, and the initial set of identified DBs was further refined into a set of drivers and a set of barriers applicable to the three technologies under study. Table 1 and Table 2 delineate the drivers identified in the systematic literature review. For each driver and barrier, the set of references in the scientific literature in which it was identified are included. The details of the process leading up to the final sets and the previous working set can be found as supplementary material.

2.2. Grey literature review

Grey literature, defined by the widely accepted Luxembourg definition, encompasses materials produced by government, academic, business, and industry entities not under the control of commercial publishers and available in various formats [45].

The systematic review of scientific literature is supplemented by information from grey literature to identify DBs and provide comprehensive definitions. The inclusion of grey literature aims to validate findings from research-based literature, offering valuable contextual information and maintaining the systematic review's rigour [46]. The precise definitions obtained for each DB make it possible to avoid ambiguity when answering the ANP questionnaires (see supplementary material). The definitions are available together with the questionnaires and the grey literature sources used for each DB are provided in Supplementary Material. Table 3 shows the identification of each DB in the grey literature.

3. Context and method

This section delves into the context and methodology of the study, providing an overview of the Spanish context concerning renewable energy and explaining the Analytic Network Process (ANP) method employed for analysis. It first explores the regulatory landscape, focusing on recent developments and policies that promote distributed renewable energy in Spain. Then, it outlines the ANP method used to identify and evaluate the main drivers and barriers associated with renewable energy technologies, ensuring a comprehensive understanding of the factors impacting their adoption in both industrial and residential sectors.

3.1. The spanish context

Spain has made significant strides in fostering the deployment of distributed renewable energy. This decentralised approach is particularly relevant in the context of diverse environmental and energy policies, including promotion schemes that Spain's regions have the autonomy to implement. The regulatory landscape underwent a notable development with the recent enactment of Royal Decree 244/2019 [60]. This Royal Decree aimed at promoting renewable energy adoption and established a comprehensive framework for deploying rooftop PV installations nationwide. Under RD 244/2019, a financial mechanism has been introduced for energy exported to the grid, providing a bill reduction associated with the electricity injected into the grid based on the hourly wholesale price and with a maximum decrease in actual consumption. Additionally, the regulatory framework supports shared self-consumption installations, allowing several consumers to collectively benefit from a single renewable energy system.

The regulatory system distinguishes between two types of installations based on their capacity and interaction with the energy market. Installations with a capacity exceeding 100 kW fall into the category of those directly selling electricity to the wholesale market, primarily industries and large companies. On the other hand, installations with a capacity below 100 kW are eligible for a simplified net billing system, facilitating a streamlined process for smaller-scale distributed energy projects, primarily residential consumers.

Given this regulatory landscape, the analysis takes a comprehensive approach, ensuring representation from various Spanish regions. Specifically, a concerted effort has been made to include experts from Catalonia, the Balearic Islands, the Valencian Region, and Madrid. This inclusive selection allows for delving into the nuances of regulatory implementation and regional characteristics affecting the adoption of distributed renewable energy in Spain. Examining the three proposed technologies (batteries, EM devices, and solar PV) alongside the different regions and types of adopters (industrial and residential) aims to provide a thorough understanding of the dynamics at play in this complex landscape.

Table 3
Drivers and barriers in the grey literature [47–59].

DE1	DE2	DE3	DE4	DI1	DI2	DI3	DS1	DS2	DS3	DS4	DT1	DT2	DT3	BE1	BE2	BE3	BI1	BI2	BI3	BS1	BS2	BS3	BS4	BT1	BT2	BT3	Reference
x	x	x	x	x	x	x	x	x	x		x	x		x	x	x				x	x	x	x	x	x	x	[47]
x			x		x							x							x					x			[48]
	x				x	x	x			x				x			x			x	x	x	x				[49]
	x						x		x			x		x						x	x	x	x				[50]
					x		x	x	x									x									[51]
						x									x	x	x		x	x		x	x				[52]
													x					x	x					x			[53]
							x	x																x			[54]
x	x				x		x	x						x													[55]
x							x							x													[56]
x			x				x	x	x	x								x									[57]
							x							x		x			x				x				[58]
									x					x													[59]

3.2. The analytic network process method

This study introduces an integrated multicriteria decision-making method using the Analytic Network Process (ANP) to identify primary DBs concerning three decentralised renewable energy technologies—batteries, EM and solar PV,—across two distinct adopter types: industrial and residential. The evaluation framework, illustrated in Fig. 1, comprises two principal stages. Several studies use MCDM as ANP to assess energy policies and decisions in complex contexts that combine qualitative and quantitative information. For instance, these methods are applied to the study of barriers to renewable energy sources at a national scale [61], the selection of technologies for rural electrification [62], and at the urban scale barriers to transport decarbonisation [63], and gender and climate criteria in urban decarbonisation policies [64].

The initial stage involves preparing the ANP models, which incorporates a comprehensive literature review (detailed in Section 2). This phase consists of a general approach, which could apply to other analyses of DBs in adopting RETs. Following the literature review, a set of DBs and definitions are compiled and shared with selected experts in a focus group session. This session aims to discuss and validate the set comprehensively.

The second stage involves resolving the models. It starts with constructing the ANP models, for drivers and barriers, followed by experts' participation in a survey designed to collect and analyse experts' judgements. The survey includes six pairwise comparison questionnaires corresponding to each ANP model network element. Subsequently, experts' responses are input into Super Decisions®software [65] for analysis following the ANP procedure. The final steps involve thoroughly assessing results to comprehensively address the research questions, detailed in the following subsections.

3.2.1. Selection of the experts

In participatory methodologies like ANP, precise expert selection is crucial for conducting effective prioritisation sessions. While a large group is not essential, their expertise should be directly relevant to the case under analysis. Stakeholders' motivations, willingness, and anticipated benefits concerning technology adoption vary significantly based on their role and energy utilisation costs [11,12]. For instance, an industrial consumer integrates energy cost as a critical factor in their production process, shaping their approach towards RET investment. Conversely, a residential consumer addresses this decision differently, with varied implications. Thus, both industrial and residential adopters warrant analysis. Expert selection should consider profiles aligned with the field and specialisation targeting either of these adopter types. Hence, the expert selection process is guided by three axes: (i) regional focus, (ii) adopter type, and (iii) the triple helix model of innovation involving academia, government, or industry.

Fifteen practitioners from academia, public sector and industry form this group of experts in renewable energy systems with experience in the residential or industrial sector. Given the context of the study and the policies that promote the adoption of RETs, the group of facilitators of the method and authors of this paper selected four representative Spanish regions that have implemented energy and economic policies to promote the adoption of RETs. This selection is intended to ensure that differences between regions are considered and an overall representation of the national case study is achieved. The mapping results of the 15 experts (E1...E15) are presented in Fig. 2.

3.2.2. Construction of the analytic network process model

The following approach is adopted to encompass the spectrum of DBs for the three RETs without compromising usability or hindering comprehensive comparisons among representative elements. From the literature review, DBs are organised into four distinct clusters based on their nature: technical, social, economic, and institutional. This clusterisation enables separate analyses of drivers and barriers for each cluster within the context of the three technologies. Fig. 3 depicts the foundational structure of the ANP network model replicated to create six models, one for each of the three technologies for drivers and likewise for barriers. Applying ANP generates weights that might mirror the prioritisation of barriers and drivers for each technology. These weights mean the relative importance of each barrier and driver within the realm of the three technologies.

3.2.3. Analytical network process

The Analytic Network Process (ANP), proposed by Saaty in 1996 [66], offers a structured approach to decision-making and evaluation, particularly beneficial when information is complex and limited. ANP demonstrates its robustness by employing a network-based model encompassing criteria (drivers or barriers) and alternatives (like RETs) grouped into clusters. This network allows for diverse relationships between elements, encompassing feedback loops and interdependencies within and across clusters, effectively capturing the complexities inherent in the evaluation process [67,68].

ANP's strength lies in its utilisation of a 1-to −9 ratio scale, facilitating the representation of various interactions between tangible and intangible criteria. These interactions are translated into weights or preferences, determined through pairwise comparisons between elements within each level. The relative importance of elements concerning their controlling criteria is gauged using this scale [66].

Saaty [66] outlines the steps involved in the ANP model:

(i) Identification of network components, elements, and their relationships.

(ii) Conducting pairwise comparisons based on ratio scales. The pairwise comparisons are conducted for the relative importance towards the control criterion and measured using Saaty's 1-to −9 scale. The score of a_{ij} in the pairwise comparison matrix represents the relative importance of the element on row (i) over the element on column (j):

$$a_{ij} = w_i / w_j \tag{1}$$

Where w_i is the weighting of the element (i). For any criterion, pairwise comparisons are performed on two levels, i.e., the element level and the cluster level comparison.

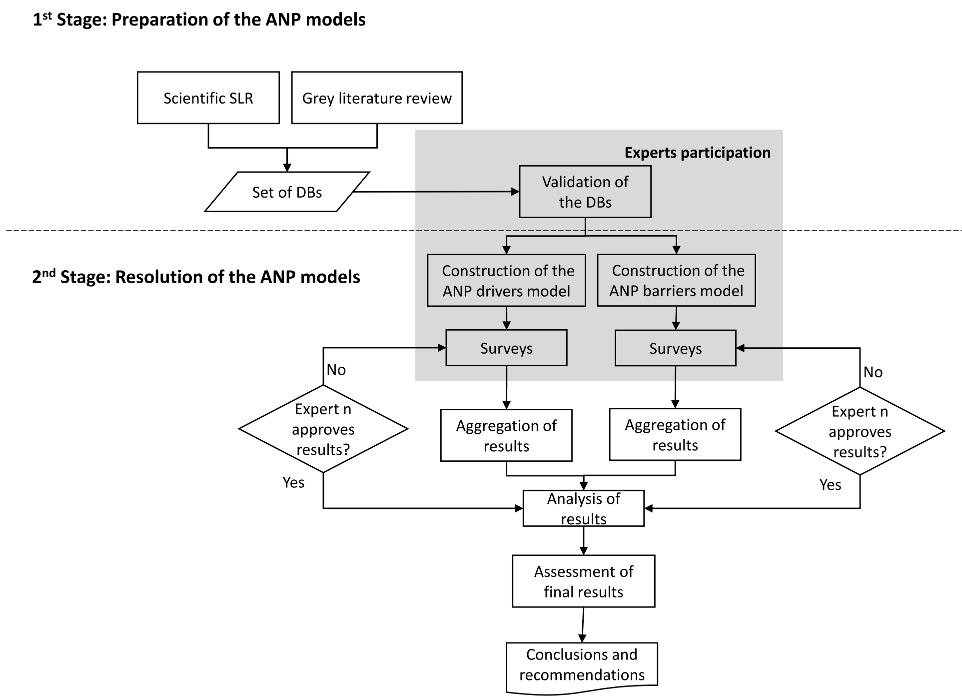

Fig. 1. Method.

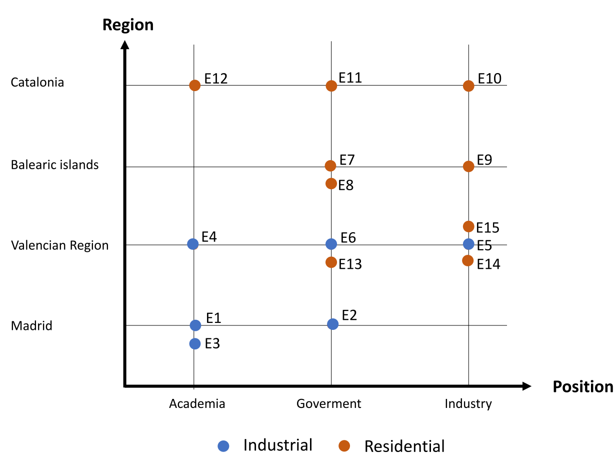

Fig. 2. Composition of the group of experts.

(iii) Incorporating resultant relative importance weights (eigenvectors) into the matrix. If there are n elements to be compared, the comparison matrix (A) is defined as:

$$A = \begin{bmatrix} w_1/w_1 & w_2/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \end{bmatrix} \tag{2}$$

After all pairwise comparisons are completed, the priority weight vector (w) is computed as the unique solution of

$$Aw = \lambda_{max} w \tag{3}$$

Where λ_{max} is the largest eigenvalue of matrix A and w is its eigenvector. The consistency index (CI) and consistency ratio (CR) of the pairwise comparison matrix could then be calculated by:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{RCI} \tag{5}$$

Where RCI is a Random Consistency Index provided by [66]. In general, if CI is less than 0.1, the judgment can be considered consistent.

(iv) Construction of the unweighted supermatrix.
The relative importance weights (eigenvectors) derived from pairwise comparison matrices are incorporated into a comprehensive supermatrix, illustrating the interconnectedness among all elements. Refer to Table 4 for details on the overall supermatrix structure, where C_i signifies the ith cluster, e_{ji} represents the jth element of the ith cluster, and W_{ik} forms a block matrix containing priority weight vectors, indicating the influence of the element in the ith cluster concerning the kth cluster.

(v) Constructing the weighted supermatrix.
The following step involves the weighting of the blocks of the unweighted supermatrix based on the respective cluster priorities, ensuring it achieves column stochasticity (weighted supermatrix).

(vi) Calculation of the global priority weights.
Iterating the weighted supermatrix through successive powers until convergence yields the limit supermatrix, wherein the weights stabilise. Each column of this matrix denotes the final weights assigned to the various elements under consideration. These weights serve as a non-dimensional measure. To enhance the significance of the outcomes, involving multiple experts in prioritisation is recommended.

3.2.4. Expert weighting though surveys

The expert prioritisation phase occurred during a comprehensive face-to-face session at the Universitat Politècnica de València on 6th July 2023. Experts were convened for a full-day session. The initial morning session started with the validation of the DBs. The DBs were thoroughly examined and deliberated to ensure unanimous agreement on the chosen criteria. Once the DBs were validated, the facilitators elucidated the ANP principles, enhancing the experts' comprehension and facilitating the clarity of the subsequent surveys. In the afternoon,

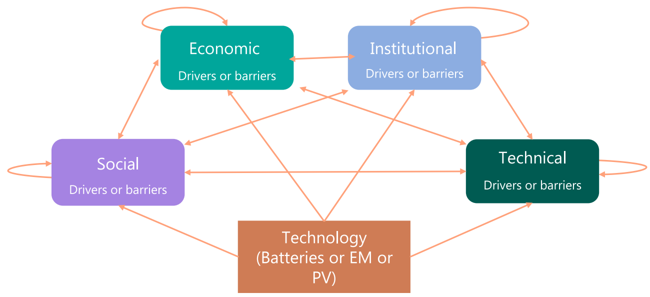

Fig. 3. Base structure of the model.

Table 4
General structure of the supermatrix.

		c_1				c_2					c_n			
		e_{11}	e_{12}	…	e_{1n}	e_{21}	e_{22}	…	e_{2n}	…	e_{n1}	e_{n2}	…	e_{nn}
c_1	e_{11}	W_{11}				W_{12}					W_{1n}			
	e_{12}													
	…													
	e_{1n}													
c_2	e_{21}	W_{21}				W_{22}					W_{2n}			
	e_{22}													
	…													
	e_{2n}													
	…													
c_n	e_{n1}	W_{n1}				W_{n2}					W_{nn}			
	e_{n2}													
	…													
	e_{nn}													

each sub-group of experts, under the guidance of facilitators, addressed their respective surveys. The answers were provided individually. Subsequently, the facilitators in charge of each sub-group aggregated them to obtain the group responses.

This structured and organised approach, involving the collaborative efforts of experts from diverse regions, ensured an understanding of the criteria and exemplified the thoughtful application of ANP principles. The subgroup division, coupled with facilitator guidance, optimised the efficiency of the survey completion process.

4. Results

This section presents the analysis outcomes, focusing on the DBs within the context of the Spanish case study. The results from each expert showcase their prioritisation of the six models, indicating their ranking of drivers/barriers for each of the three technologies.

An aggregation method using average (geometric) values has been employed to synthesise individual expert perspectives. The discussion of the results is systematically structured to address the three pivotal research questions. Specifically, RQ1 focuses on discerning the most influential drivers and barriers impacting the adoption of decentralised RET. Meanwhile, RQ2 and RQ3 investigate potential variations in these drivers and barriers regarding the specific technology and whether the significance of these drivers and barriers is contingent upon the type of adopter and the specific geographical context.

To delve into these questions, the prioritisation results for drivers and barriers are presented in Sections 4.1 and 4.2, respectively. Within these sections, a detailed analysis of the aggregated results is conducted. The aggregation is performed for the general prioritisation (independent of the type of technology and adopter) to respond to RQ1, and separately for each of the six models, to respond to RQ2 and RQ3 concerning the differences depending on the technology, adopter and geographical context. The section also explores the interactions among the primary drivers, examining how they influence one another. Similarly, the impacts of the main barriers on each other are scrutinised in this section. Finally, Section 4.3 discusses the relationships between the primary drivers and barriers.

4.1. Drivers prioritisation

The overall results of driver prioritisation are presented in Fig. 4. Three drivers, political will (DI2), technological maturity (DT2) and fiscal and economic incentives (DE1) emerge across technologies and adopter types. Items that contribute a minimum of 10% to the total weight have been selected as the primary ones. These three drivers together account for 41% of the total prioritisation weight. While the remaining economic drivers demonstrate moderate importance, those within the social cluster receive comparatively less emphasis than the other clusters (institutional, technical, and economic). These three primary drivers converge into a central concept, steering the trajectory of decentralised RETs. The maturation of technologies plays a pivotal role in fostering the adoption of RETs. Attaining this maturity necessitates political intention, commitment, and fiscal and economic incentives that nurture their development until they reach a consolidated state of maturity. Additionally, highlighting another key insight is essential: the intricate interplay among different driver types - economic, institutional, and technical. Recognising how these factors synergise is fundamental for a comprehensive understanding of the dynamics influencing the adoption of decentralised RETs.

The detailed analysis delves into variations based on technology type, adopter characteristics, and geographical regions, as illustrated in Fig. 5 and Fig. 6.

Observations indicate minimal disparities associated with technology type, adopter category, or regional context. In this sense, the most notable differences are found according to the adopter type, for example, in the case of Fiscal and economic incentives (DE1), Adopter's motivation (DS3) and Transposition of European directives (DI1) (Fig. 5). Fiscal and economic incentives (DE1), for instance, emerge as somewhat more influential for residential adopters than their industrial counterparts, for solar PV and batteries. However, for EM, a cheaper type of technology, the slightly lower importance of this driver compared to the other technologies is more remarkable than the differences between residential and industrial adopters,

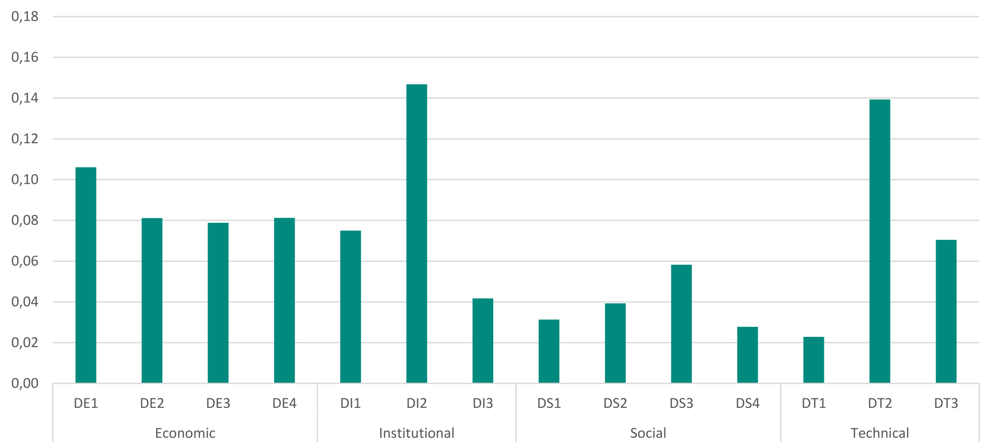

Fig. 4. Overall results of the prioritisation of drivers.

which loses importance. Other drivers such as Existing infrastructure (DT1), Development of infrastructures and uses (DT3) and Rejection of dependence on third parties (DS2) show no noticeable differences. The weighting scores are generally relatively homogeneous regarding the differences by region and technology (Fig. 6). Some cases show differences between standard technologies in the different regions, e.g. Environmental charges (DE3), which show higher importance for EM in all regions than the other two technologies. While there are cases such as the Stabilisation of low energy prices DE4 that show a higher value for one region, for Madrid, the importance is significantly higher for batteries and EM. Still, it follows a coherent order concerning the other regions in the order by technology (more importance for batteries, then EM and lastly PV).

Despite these nuanced distinctions, the findings reveal a lack of substantial variations based on adopter type, region, or technology. The main drivers coincide independently of these three axes, which strengthens the finding.

Experts envision the promotion of decentralised RETs as a collective endeavour. Despite differences in technology characteristics, adopter types and their objectives, and territorial disparities and competencies of local administrations, achieving technological maturity with political will and fiscal and economic incentives is the collective vision for promoting decentralised RETs. Regional differences might be scarce because despite having developed regional laws, the predominant influence of national-level legislation and the EU framework strongly impact this situation.

An additional outcome derived from the ANP is the assessment of how specific drivers influence others. These influences are determined by creating an aggregated weighted supermatrix (Step V in 3.2.3, Analytical Network Process method). The weighted supermatrix, detailed in Table 5, encapsulates the collective impact of each driver on every other driver(on a pairwise basis). Notably, the highlighted entries in the matrix signify influences surpassing a threshold defined as the mean plus two times the standard deviation.

Noteworthy from this analysis is the identification of six drivers wielding significant influence over others. Specifically, political will (DI2), technological maturity (DT2), stabilisation of low energy prices (DE4), fiscal and economic incentives (DE1), and adopter's motivation (DS3) emerge as the most influential. Turning to the prioritisation results (refer to Fig. 4), a correlation becomes evident: two of the most influential drivers, political will and technological maturity, also claim the utmost importance. Political will, for instance, impacts access to sufficient funding (DE2), environmental charges (DE3), transposition of EU directives (DI1), and awareness and education (DS2). Consequently, bolstering these primary drivers can positively influence other drivers within their sphere of influence in a cascade effect.

4.2. Barriers prioritisation

This section presents an analysis of the prioritisation of barriers that hinder the development of each technology. Fig. 7 shows the overall results of the obstacles prioritisation. The main barriers are techno-economic uncertainty (BT2), inadequate electricity tariff structure (BE2), lack of technical definition and standardisation (BI1), lack of know-how (BS4), and institutional inertia (BI2). Items that contribute a minimum of 10% to the total weight have been selected as the primary ones. These five barriers together account for 65% of the total prioritisation weight. Each cluster has at least one prominent barrier: economic, institutional, social, and technical. Unlike the results for the main drivers, the barriers are more diverse and need to be addressed from various perspectives.

Some disparities emerge when considering specific technologies. For example, the inadequate electricity tariff structure (BE2) is more pronounced in EM devices when contrasted with solar PV panels or batteries since improvements in electricity tariff structures will allow for the most significant savings when implementing EM (Fig. 8. This difference between technologies is more remarkable for residential than for industrial adopters. The electricity tariff structure is more important for industrial adopters since they can benefit from economies of scale and tend to have a more rational investment approach. Moreover, there is more distinction between technologies for these adapters. Fig. 9 shows that the main barriers are not as clear as the main drivers. If we compare Fig. 6 and Fig. 9 we observe a greater dispersion of the results in the case of the barriers.

The Institutional Inertia Barrier (BI2), although of similar importance for both types of adopters and the three technologies, is more important for batteries than for solar PV and EM in the case of industrial adopters. However, for residential adopters, energy management is more important. This points to a greater need for institutional promotion of batteries in the industrial sector and for promoting EM in the residential sector.

Table 6 shows the weighted supermatrix, presenting the aggregated value of the influence of each barrier against each other. The two main barriers (see Fig. 7), inadequate electricity tariff structure (BE2) and techno-economic uncertainty (BT2), are also the most influencing ones. Table 6 also shows that two other barrier items, economic profitability (BE3) and lack of technical definition and standardisation (BI1), also have a strong influence on other barriers.

The inadequate electricity tariff structure strongly influences the lack of technical definition and standardisation (BI1). At the same time, techno-economic uncertainty (BT2) has a strong influence on the lack of technical definition and standardisation, as well as on investment costs (DE1) and space issues (BT1). The two main barriers that influence the lack of technical definition are the lack of energy awareness (BS3)

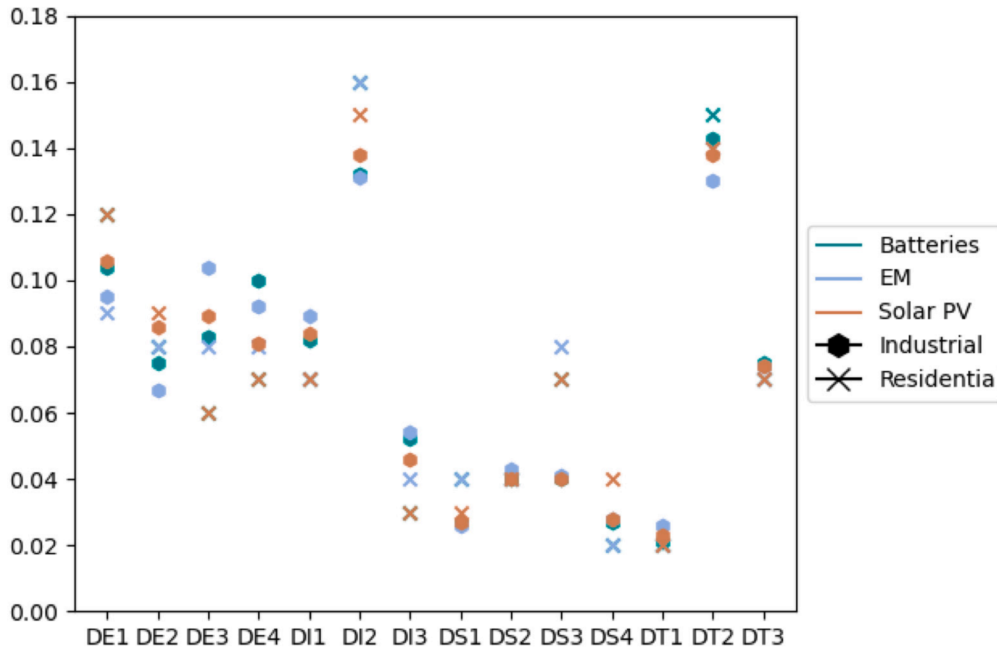

Fig. 5. Overall results of the prioritisation of drivers by technology and adopter.

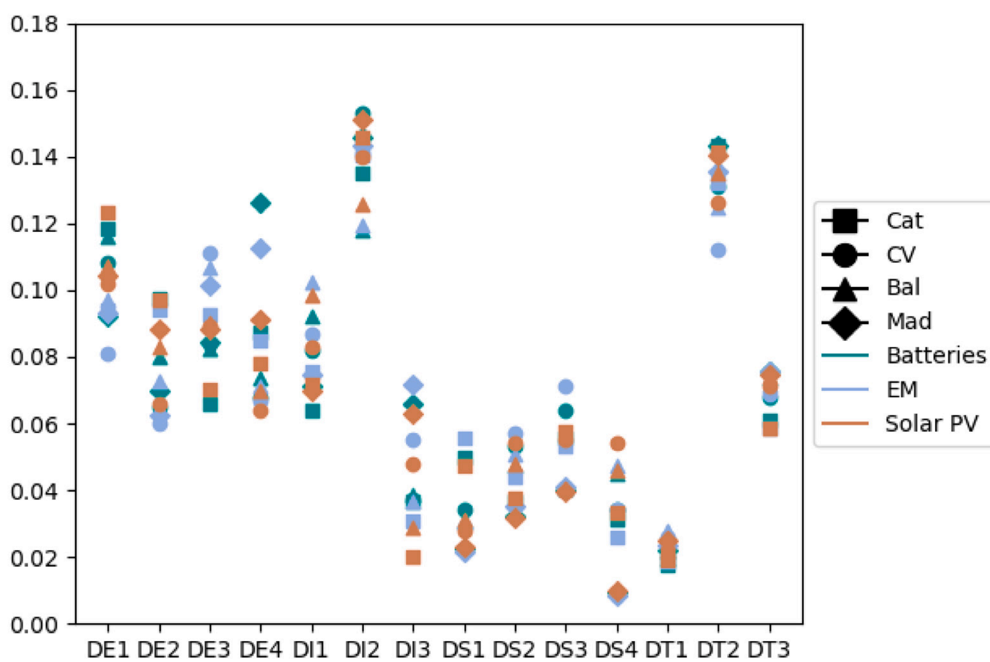

Fig. 6. Overall results of the prioritisation of drivers by technology and region.

and space issues (BT1). As a result, addressing the primary barriers will reduce the impact of several other economic, institutional, and technical barriers.

4.3. Contrasting drivers and barriers

The analysis has been conducted separately for drivers and barriers to delve into the limiting aspects of adopting RET. However, upon concluding this analysis, some conclusions can be drawn regarding the mirroring effect that may occur between both categories. Some drivers to adopting RETs might contribute to attenuating particular barriers.

Regarding the main barrier, techno-economic uncertainty (BT2), investing in RET can be challenging due to rapid fluctuations in technology prices (mainly decreasing) or market model performance improvements. Additionally, variations in electricity prices and political changes make it complex to forecast long-term revenue and costs in energy markets. For instance, an explosion in Solar PV occurred in Spain in 2018 due to policy changes and increased subsidies. The energy crisis and record electricity prices boosted this. However, when energy prices returned to normal levels, the adoption rate, particularly in the residential sector, stabilised after years of exponential growth. Against this background, some drivers to adoption can play a particularly significant role in attenuating this specific barrier. For instance, greater technological maturity (DT2) contributes to reducing

Table 5
Drivers' aggregated weighted matrix. Bold values are above the average plus two times the standard deviation.

	DE1	DE2	DE3	DE4	DI1	DI2	DI3	DS1	DS2	DS3	DS4	DT1	DT2	DT3
DE1	0,00	**0,25**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,09	0,00	0,00	0,16	0,00
DE2	0,11	0,00	0,00	0,09	0,00	0,08	0,00	0,00	0,00	0,05	0,00	0,00	0,11	0,00
DE3	0,07	0,00	0,00	0,16	0,15	0,07	0,09	0,00	0,00	0,03	0,00	0,00	0,06	0,00
DE4	0,07	0,00	0,00	0,00	0,10	0,05	0,11	0,20	**0,25**	0,03	0,00	0,00	0,00	**0,25**
DI1	0,00	0,00	0,15	0,08	0,00	0,20	0,11	0,00	0,00	0,04	0,00	0,00	0,00	0,15
DI2	0,16	**0,25**	**0,35**	0,17	**0,25**	0,00	0,09	0,20	**0,25**	0,09	0,00	0,00	0,00	0,00
DI3	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,10
DS1	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,00	0,00	0,11	0,00	0,00	0,00	0,00
DS2	0,00	0,00	0,00	0,00	0,11	0,05	0,03	0,13	0,00	0,04	0,20	0,00	0,00	0,00
DS3	0,00	0,00	0,00	0,00	0,14	0,08	0,06	0,07	**0,25**	0,00	0,13	0,00	0,00	0,00
DS4	0,00	0,00	0,00	0,00	0,00	0,07	0,00	0,00	0,00	0,05	0,00	0,00	0,00	0,00
DT1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,09	0,00	0,00	0,00	0,17
DT2	**0,25**	**0,25**	0,00	0,14	0,00	0,20	0,09	0,20	0,00	0,11	**0,33**	0,00	0,00	0,08
DT3	0,00	0,00	0,00	0,11	0,00	0,00	0,11	0,00	0,00	0,00	0,00	0,00	**0,33**	0,00

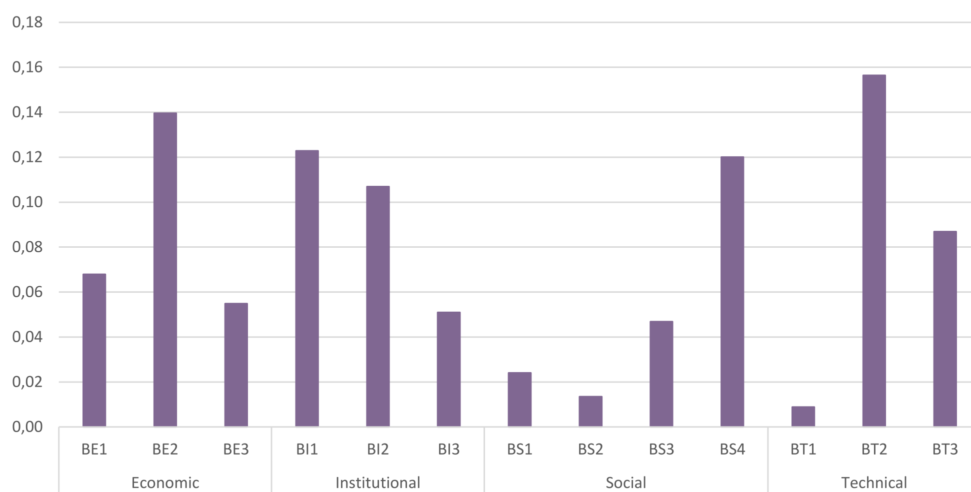

Fig. 7. Overall results of the prioritisation of barriers.

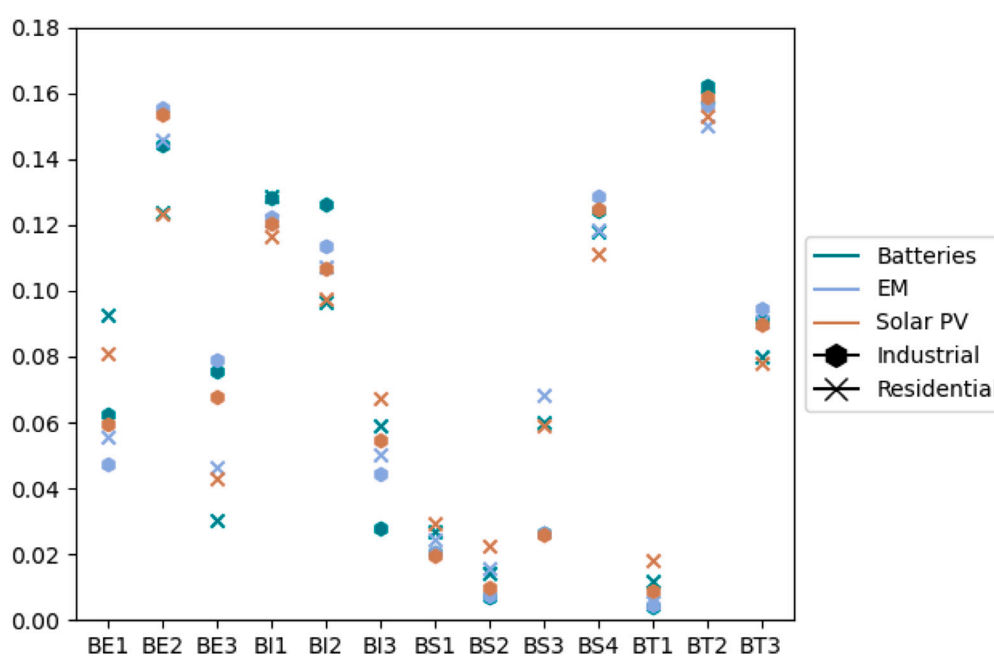

Fig. 8. Overall results of the prioritisation of drivers by technology and adopter.

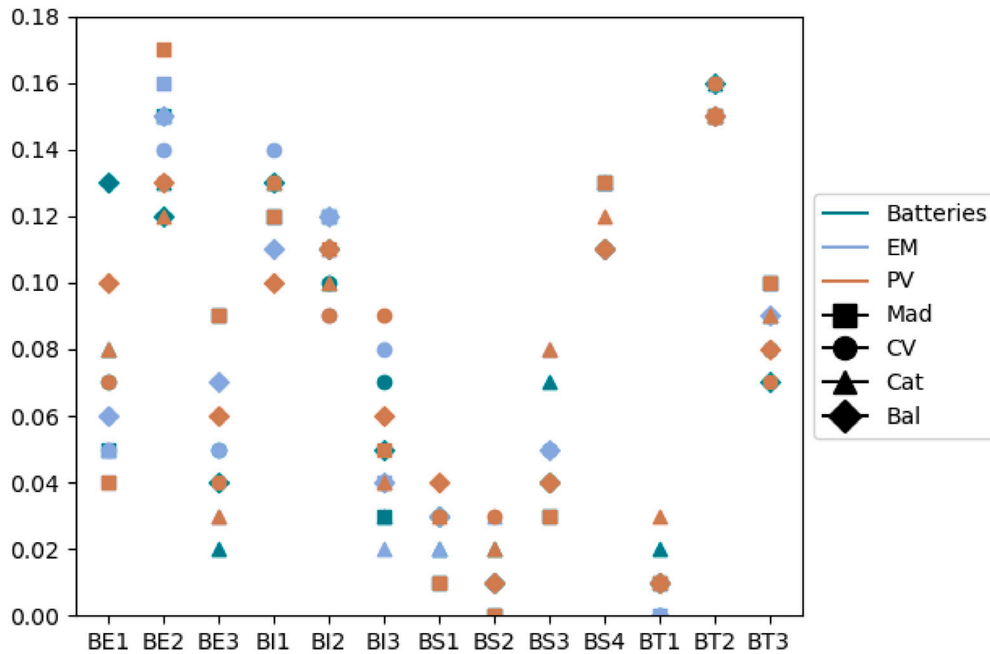

Fig. 9. Overall results of the prioritisation of barriers by technology and region.

Table 6
Barriers' aggregated weighted matrix. Bold values are above the average plus two times the standard deviation.

	BE1	BE2	BE3	BI1	BI2	BI3	BS1	BS2	BS3	BS4	BT1	BT2	BT3
BE1	0,00	0,00	0,11	0,00	0,00	0,00	0,08	0,00	0,13	0,08	0,00	0,09	0,00
BE2	0,00	0,00	0,09	**0,25**	0,20	0,20	0,04	0,00	0,00	0,12	0,00	0,11	0,20
BE3	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,20	0,12	0,00	**0,25**	0,00	0,00
BI1	0,11	0,00	0,00	0,00	0,20	0,08	0,00	0,14	**0,25**	0,20	**0,25**	0,20	0,00
BI2	0,09	0,20	0,20	0,19	0,00	0,12	0,09	0,00	0,00	0,00	0,00	0,00	0,20
BI3	0,13	0,05	0,00	0,06	0,00	0,00	0,11	0,06	0,00	0,00	0,00	0,00	0,00
BS1	0,00	0,00	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,09	0,00	0,00	0,00
BS2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06
BS3	0,00	0,09	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,11	0,00	0,00	0,00
BS4	0,00	0,16	0,11	0,00	0,20	0,20	0,20	0,12	0,00	0,00	0,00	0,20	0,14
BT1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,13	0,00	0,00	0,00	0,00	0,00
BT2	**0,33**	0,16	0,00	**0,25**	0,20	0,20	0,14	0,00	0,12	0,08	**0,25**	0,00	0,20
BT3	0,00	0,09	0,20	0,00	0,00	0,00	0,06	0,07	0,13	0,12	0,00	0,20	0,00

and minimising technology costs, making this factor less uncertain and promoting greater stability in energy prices. Furthermore, greater fiscal and economic incentives (DE1) could favour adopters' decisions to enhance technological maturity, reinforced by increased stability and political commitment (DI2) to decentralised energy policies for promoting RET.

Similarly, the second most significant barrier, inadequate electricity tariff structure (BE2), is likely attenuated by a range of drivers to adoption. This includes favouring market participation mechanisms (DI3), a driver not highlighted as primary. Additionally, this barrier comprises inequality related to the benefits of prosumerism between tenants and landlords, requiring, among other things, political willingness (DI2) to establish regulations addressing these inequalities. Also, the lack of technical definition and standardisation (BI1) is mainly related to political will (DI2) and the transposition of European directives (DI1). A clear and specific framework is needed for decentralised RET installation, operation, and integration with the electrical grid. The lack of know-how (BS4) is related to knowledge of RET and their technical and administrative implementation processes. For this, the previously mentioned clear and specific framework is essential, along with the transmission of information to potential adopters and professionals in the sector through clear, reliable, and accessible information (DS1) and awareness, education, and training programs (DS2), along with the promotion of pilot projects that encourage learning. Finally, since institutional inertia (BI2) results in a lack of action regarding regulatory and energy policies, unlocking this situation requires greater political commitment (DI2) to the regulatory needs of decentralised RET.

It can be concluded that the highlighted drivers could contribute to reducing critical barriers. To promote decentralised RET, it is necessary to demonstrate whether there is a correlation between the main drivers and barriers and to study whether the elimination or promotion of one produces effects and feedback loops into the others.

5. Discussion

This study and the proposed method contribute to identifying, from a holistic perspective, the drivers and barriers of decentralised renewable technologies by leveraging the expertise of sector professionals. It is worth noting that the main drivers (DBs) identified in the study largely do not coincide with those found most frequently in the literature. Two main drivers identified in this study, political will (DI2) and technological maturity (DT2), do not stand out among those identified most frequently in scientific literature. However, political will (DI2) does recur in grey literature. The recurrence of the DBs in the reviewed literature can be observed in Table 1 and Table 2 for scientific literature and in Table 3 for grey literature. Fiscal and economic incentives (DE1), the third driver in the study's prioritisation, align with those most frequently found in scientific literature. Regarding the main barriers, only the lack of technical definition and standardisation (BI1) ranks among those found most frequently in the reviewed literature. The holistic perspective and the expertise of professionals working in various positions within the energy sector highlight that the main DBs are not being identified in most of the analysed literature on decentralised RETs, while some of the mostly identified DBs are of lesser relevance. This underscores the importance of considering diverse sources of information and practical experiences when analysing the drivers and barriers of decentralised renewable technologies.

The main drivers of these technologies involve achieving technological maturity fostered by political will and fiscal and economic incentives. In general, those identified as primary drivers are consistently among the top regardless of adopter type, region, or technology, although some exhibit greater variability than others across these dimensions. However, the situation is more diverse when it comes to the main barriers to overcome. The prioritisation of barriers shows greater dispersion across the three categories than drivers. This suggests that while certain barriers may be universally recognised, a wider range of challenges must be addressed, each with its own unique characteristics and implications. Thus, formulating effective strategies to overcome these barriers requires a more nuanced and context-specific approach than that required for addressing the drivers.

The cascade effect observed in the study highlights the interconnection between the different identified drivers. This phenomenon demonstrates how the presence or absence of certain drivers can influence the emergence or attenuation of others, underscoring the importance of addressing them comprehensively. Political will, for instance, impacts access to sufficient funding (DE2), environmental charges (DE3), transposition of EU directives (DI1), and awareness and education (DS2). Consequently, bolstering these primary drivers can positively influence other drivers within their sphere of influence in a cascade effect. The same applies to the barriers; moreover, an interaction exists between drivers and barriers. For instance, techno-economic uncertainty challenges RET investment due to fluctuating technology prices and market performance. Yet, factors like technological maturity and fiscal incentives alleviate this uncertainty.

Similarly, inadequate electricity tariff structures are countered by drivers like market participation mechanisms and political willingness to address inequalities. Standardisation issues and lack of know-how also require clear frameworks and educational efforts. Institutional inertia further impedes regulatory action, necessitating greater political commitment. Addressing these drivers may help overcome critical barriers, highlighting the need for further research on their interplay and effects. Addressing these drivers in a coordinated manner can maximise their effectiveness and accelerate the transition towards a more sustainable and decentralised energy system.

The analysis conducted in three axes — technologies, adopters, and regions — underscores the importance of tailoring policies to different adopter profiles and, to some extent, to different technologies. The low relevance of differences in regional analyses is consistent with the overarching framework of the EU, where common policies and regulations diminish regional disparities. This underscores the need for policy interventions to address specific barriers and harness drivers across various segments to facilitate the widespread adoption of decentralised RETs across Europe.

However, it is important to acknowledge several limitations within this study. For instance, the stakeholder perspective is primarily focused on the case of Spain. Therefore, it is crucial to recognise that the specifics and values of this particular case cannot be directly extrapolated to Europe as a whole. However, assuming that general trends can be extrapolated, the study offers valuable insights into the overarching drivers and barriers shaping the renewable energy landscape within the EU. Additionally, while a comprehensive analysis was conducted across three dimensions (technologies, adopters, and regions), other variables may not be considered that also influence the adoption of these technologies. Moreover, generalising the results to other regions outside Spain and the EU must be cautiously approached, as local conditions and policies may vary considerably. For this reason, future work is necessary to replicate the study in countries with contexts different from the European framework and to analyse in detail the main barriers, such as technical and economic uncertainty, to address them and promote decentralised RETs.

6. Conclusions

The shift towards an economy propelled by renewable energy technologies presents various challenges across environmental, technical, economic, social, and regulatory spheres. This research delves into the nuanced landscape of adopting decentralised RET. Employing a Multicriteria Decision-Making Method, the significance of drivers and barriers is systematically assessed using the ANP. This method entails selecting and grouping decision criteria, followed by analysing interactions within the network model.

The study focuses on Spain and encompasses batteries, EM devices, and solar PV for both industrial and residential adopters. It reveals that political will (DI2), technological maturity (DT2), and fiscal and economic incentives (DE1) emerge as paramount drivers. These three drivers together account for 41% of the total prioritisation weight. These core drivers coalesce around a central idea—the need for mature technologies to expedite RET adoption. Achieving this maturity necessitates political dedication, commitment, and fiscal and economic incentives, guiding their development towards consolidation.

Conversely, techno-economic uncertainty (BT2) leads the list of primary barriers, trailed by the inadequacy of the electricity tariff structure (BE2). Additional barriers, such as the lack of technical definition and standardisation (BI1), absence of know-how (BS4), and institutional inertia (BI2), highlight challenges across economic, institutional, social, and technical realms. These five barriers together account for 65% of the total prioritisation weight. Unlike the more uniform landscape of drivers, addressing barriers requires a multifaceted approach and poses a challenge for specific policy recommendations. However, the analysis reveals intricate interdependencies among the main drivers and barriers, showcasing a cascade effect wherein fortifying primary drivers positively influences others within their domain. This pattern is mirrored in the barrier domain.

Furthermore, the study shows that the primary DBs for decentralised RETs remain consistent across technologies, adopter types, and regions. While nuanced differences exist, the convergence of primary barriers and drivers suggests a unified approach in policy design and promotion efforts. The diminished importance of differences in regional analyses aligns with the overarching framework of the EU, where uniform policies and regulations mitigate regional disparities. Consequently, the findings of this study extend beyond Spain's borders, particularly within the EU context.

In essence, the identified drivers serve as catalysts for RET promotion and exhibit the potential to alleviate the primary barriers. To propel decentralised RETs forward, exploring the relationship between critical drivers and barriers is imperative. Understanding how the enhancement or removal of one factor may influence others is essential for crafting effective strategies that foster the widespread adoption of decentralised RETs.

While this study offers valuable insights into adopting decentralised RETs in Spain, it has limitations. One limitation is the focus on a single country, which may limit the generalisability of the findings to other regions with different socio-economic and regulatory environments. Future research should consider a comparative analysis across multiple countries to validate and expand upon the findings. Furthermore, the dynamic nature of technological and policy advancements means that the drivers and barriers identified in this study may evolve. Future research should track these changes and their impacts on RET adoption.

CRediT authorship contribution statement

I. Aparisi-Cerdá: Writing – original draft, Visualization, Methodology, Data curation. **D. Ribó-Pérez:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Data curation. **M. García-Melón:** Writing – review & editing, Supervision, Methodology. **P. D'Este:** Writing – review & editing, Supervision, Conceptualization. **R. Poveda-Bautista:** Writing – review & editing, Methodology, Conceptualization.

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

Supplementary Material.

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

While preparing this work the authors used Grammarly and ChatGPT to avoid grammatical and spelling errors and improve the quality of writing. 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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2024.132264.

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