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ORIGINAL PAPER

Differences in the perception of drivers and barriers to the adoption of decentralised renewable energy technologies: a comparison between Spain and Colombia

I. Aparisi-Cerdá[1] · D. Ribó-Pérez[2] · M. García-Melón[1] · H. Gonzalez-Urango[1] · I. Ligardo-Herrera[3]

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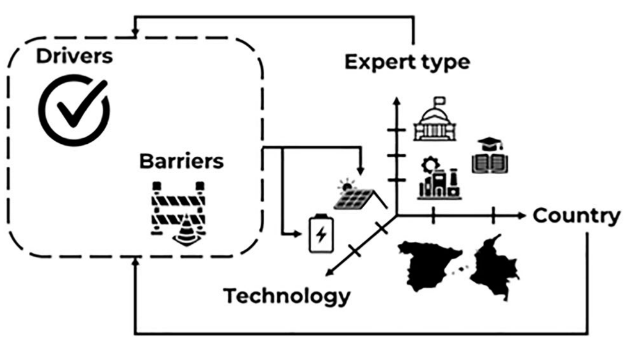
Abstract

This research examines the drivers and barriers influencing the adoption of decentralised renewable energy technologies such as rooftop photovoltaic solar systems and consumer battery energy storage systems. Using the analytic network process, expert input from government, academia, and industry was used to prioritise a range of social, economic, institutional, and technical factors in both countries. The results show that while fiscal incentives and stabilised energy prices are common drivers in both contexts, Colombia faces stronger economic and technical barriers, such as limited access to funding and techno-economic uncertainty. Conversely, Spain's decentralised energy transition is primarily hindered by techno-economic uncertainty, challenges related to the electricity tariff structure, and the lack of technical definition and standardisation. This comparative analysis offers novel insights into expert-based priorities across two contrasting national contexts. Based on the findings, it is recommended that Colombia focus on enhancing access to finance and strengthening regulatory clarity, while Spain should refine existing frameworks and simplify technical procedures to facilitate the scaling up of RET adoption.

Graphic abstract



Keywords Renewable energy · Barriers · Drivers · ANP · Colombia · Spain

✉ I. Aparisi-Cerdá
isapcer@upvnet.upv.es

[1] INGENIO (CSIC-UPV), Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, Spain

[2] IIE, Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, Spain

[3] Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands

Introduction

The global energy landscape is undergoing a profound transformation driven by the imperative to mitigate climate change and achieve sustainable development goals. Central to this transformation is the adoption of renewable energy sources (RES), which offer a promising pathway towards decarbonising the energy sector and limiting global temperature rise to 1.5ºC, as outlined by the International Renewable

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Energy Agency (IRENA 2021). Unlike conventional fossil fuel-based technologies that rely on centralised infrastructure, Renewable Energy Technologies (RET) enable decentralised deployment, revolutionising the traditional energy paradigm.

Decentralised or distributed energy systems, characterised by electricity generation close to the point of use, have emerged as a key component of the energy transition. The implementation of decentralised RET is influenced by factors such as technology readiness levels, stakeholder motivations, and regulatory dynamics. For instance, while solar photovoltaic (PV) technology has experienced significant cost competitiveness (Ribó-Pérez et al. 2019) and social acceptance, storage systems still face challenges in terms of cost competitiveness (Gallego-Castillo et al. 2021). Furthermore, the motivations and expectations of technology adoption vary among different types of stakeholders (Jacksohn et al. 2019; Crago and Koegler 2018).

Despite their challenges, decentralised systems offer numerous advantages over centralised counterparts, including enhanced energy autonomy, resilience to natural disasters, improved energy access for local communities, and economic empowerment of marginalised regions (Nadeem et al. 2023), they also face challenges such as larger upfront cost, citizens investments or unclear regulatory frameworks. Understanding the drivers and barriers (DBs) to adoption is crucial for policymakers, researchers, and industry stakeholders to formulate effective strategies and policies to accelerate the transition towards decentralised renewable energy systems.

The growing prominence of decentralised renewable energy systems (RES) is evident in the exponential increase in capacity witnessed over the past decade. For instance, the global capacity of distributed solar PV systems surged from 35 GW in 2017 to 107.4 GW in 2022 (IEA 2023). Nonetheless, the shift towards decentralised systems exhibits a heterogeneous pattern across various regions and nations, with noteworthy contributions emanating from China, Asia-Pacific countries, Europe, and North America, highlighting the contextual nuances inherent in energy transitions (IEA 2019).

While numerous studies have explored DBs in renewable energy adoption, most are limited to specific sectors or technologies. For example, work on decentralised systems often concentrates on niche sectors such as mining (Strazzabosco et al. 2022) and water (Strazzabosco et al. 2021) or small and medium-sized enterprises (Jalo et al. 2021), while other research isolates technologies like Battery Energy Storage Systems (BESS) (Retna Kumar and Shrimali 2021) or energy efficiency and demand response mechanisms (Wohlfarth et al. 2020). Similarly, investigations into solar self-consumption (Charters and Heffernan 2020) or community energy business models (Stauch and Vuichard 2019) tend to focus on single-policy environments, especially within the EU. In this regard, Shivakumar et al. (2019) provide an assessment of the drivers and barriers for renewable energy deployment in the EU. Yet, their analysis is limited to the European policy context and does not account for contrasting institutional, socio-economic or technological conditions in other regions.

These studies rarely integrate cross-technology or cross-contextual comparisons. As a result, there is a lack of comprehensive analyses that consider how DBs vary between national and regulatory settings. Moreover, the interdependencies between drivers and barriers, such as how institutional support can mitigate economic obstacles, are often underexamined. This study addresses these gaps by examining two countries that exemplify contrasting decentralisation pathways: one with a consolidated regulatory framework and widespread adoption of RETs, and another with emerging policies, regional disparities, and limited deployment. This comparative approach enables a broader understanding of how contextual differences shape the adoption of decentralised renewable energy technologies.

Building on a prior case study conducted within the same research project (Aparisi-Cerdá et al. 2024), this article broadens the analytical scope by including Colombia as a comparative case. Spain's regulatory maturity and market development contrast with Colombia's emerging framework, marked by regional energy disparities, limited adoption of decentralised RETs, and evolving policies.

By comparing these two diverse contexts, the analysis aims to uncover how key factors such as institutional maturity, economic development, and regulatory frameworks influence perceptions and prioritisation of drivers and barriers (DBs). Using the analytic network process (ANP), expert perspectives on the most relevant DBs associated with solar PV and BESS technologies are evaluated. This approach enables the identification of context-specific and cross-cutting factors, offering strategic insights for evidence-based policy design.

To guide this analysis and its contribution to policy design, the study is structured around the following research questions:

RQ1. How do differences in institutional, economic, technical, and social contexts influence the drivers and barriers to the adoption of decentralised renewable energy technologies?

RQ2. What are the implications of these differences for the design of effective and context-sensitive energy policies and regulatory frameworks?

The rest of the paper is organised as follows: section "Comparative energy policy context: Spain and Colombia" presents the renewable energy context for both countries, while section “Methods” presents the methods employed. Section “Results” shows the results from the analysis and their implications. Finally, section “Conclusions” concludes by summarising the main findings of the study.

Comparative energy policy context: Spain and Colombia

The countries selected for comparison, Spain and Colombia, represent different regulatory, economic, and infrastructural contexts in relation to the adoption of decentralised RETs. Spain, embedded in the EU policy framework, has developed advanced mechanisms for RET integration, while Colombia, an emerging economy, is still consolidating its regulatory and market structures. Comparing these two cases enables the analysis of how contextual differences influence drivers and barriers (DBs), providing insights into both consolidated and developing decentralisation pathways.

Colombia

The Colombian electrical mix is characterised by combination of 65% from hydroelectric generation and 35% from thermal sources. This composition relies heavily on water resources, which implies a high vulnerability to climate variability and long-term climate change. While 96–98% of the population in interconnected areas have access to electricity, the non-interconnected zones (ZNI)—which cover more than half of the country—face significant service constraints, with only 38% receiving a continuous supply. Rising tariffs and low service quality indicators further underline the need for greater state intervention and reform of a market that remains largely dominated by private actors (Ministerio de Minas y Energía de Colombia 2023).

Colombia has increasingly promoted distributed renewable energy to diversify its energy mix and reduce reliance on fossil fuels. Law 1715 of 2014 (Congreso de Colombia 2014) marked a major step by establishing a regulatory framework for RET deployment. However, despite this progress, significant barriers to adoption remain (Gómez-Navarro and Ribó-Pérez 2018). Through this Law, Colombia has introduced economically incentivised mechanisms to encourage the adoption of distributed renewable energy systems. For instance, renewable energy producers are rewarded for the energy they export to the grid. Additionally, the regulatory framework supports shared self-consumption installations, enabling multiple consumers to benefit collectively from a single renewable energy system.

In addition, since 1994, the Colombian government has created the Energy and Gas Regulatory Commission (CREG) to regulate the activities of public utilities (Congreso de Colombia 1994a, b). CREG operates independently, ensuring the efficient functioning of Colombia’s energy markets while promoting fair competition and consumer protection. Operating independently, CREG oversees tariff-setting, licensing, market rules, and technical standards, while promoting transparency, competition, and investment—key to ensuring a stable and efficient energy sector. At that time, the institutional framework did not yet include provisions for renewable energy or decentralised systems, which only began to be formally addressed two decades later through Law 1715 of 2014.

While Law 1715 of 2014 (Congreso de Colombia 2014) provides the overarching legal framework for renewable energy promotion, the regulatory agency CREG plays a vital role in translating and operationalizing the objectives set forth by the legislation into actionable regulations, overseeing their implementation, and ensuring compliance within the energy sector.

Colombia’s regulatory system also distinguishes self-generation activities between (1) Large-scale self-generators: (2) Large-scale (AGGE) with systems over 1 MW and (3) Small-scale (AGPE), with systems up to 1 MW, producing electricity mainly to meet their own needs (CREG 2015). AGPEs are also divided into those ≤ 100 kW and those between 100 and 1000 kW. Resolution CREG 174 of 2021 (CREG 2021) regulates the operational and commercial aspects to allow the integration of AGPE and distributed generation into the National Interconnected System, establishing simplified procedures for grid connection. These allow users to reduce their energy bills and sell surplus electricity. These systems benefit from simplified net billing, improving access for households and small businesses. However, the level of adoption is low (Rodríguez-Urrego and Rodríguez-Urrego 2018). There are many barriers, such as lack of knowledge and access to technology, that are slowing the adoption of these models (Morales et al. 2015).

In pursuing a fair energy transition, initiatives are proposed to reduce energy poverty, where small-scale self-generation programs play a crucial role. A considerable expansion in renewable generation capacity is required to meet the growth in demand without increasing greenhouse gas emissions. The target for 2032 aims for a diversified matrix: 35% hydro, 39% solar, 17% thermal, and 9% wind, compared to just 4% solar today. Achieving these goals will require not only to triple the installed capacity in renewable energies but also to strengthen the regulatory and normative framework to allow these sources to be integrated efficiently into the national mix (Campillo 2024; Ministerio de Minas y Energía de Colombia 2023).

The most recent regulatory development in Colombia's distributed energy policy is the implementation of Energy Communities, first introduced through Decree 2236 of 2023 (Decreto 2236 2023) and subsequently put into operation through CREG Resolution 101 072 (Resolución No. 101

072 2025), issued in April 2025. The decree established the legal recognition of Energy Communities as a distinct market actor, created a national registry and ordered CREG to define their technical and commercial frameworks. Two years later, the resolution specified maximum generation thresholds (up to 1 MW for collective self-generation and 5 MW for distributed community generation), modalities for compensation of surplus energy and interoperability rules with grid operators. It also introduced simplified procedures for community projects in rural and non-interconnected areas (ZNI), with special provisions for vulnerable populations. This regulatory package aims to reduce administrative and technical barriers to the formal participation of community energy initiatives in Colombia's decentralised transition.

Spain

Spain has made significant strides in promoting the adoption of distributed RES, driven by a strong policy and regulatory environment within the broader EU framework. The Spanish energy transition strategy emphasises decentralisation, sustainability, and citizen participation.

This decentralised approach is particularly pertinent given Spain's diverse environmental and energy policies, empowering regions with the autonomy to implement tailored promotion schemes.

Spain had installed nearly 7 GW of rooftop solar PV and 1,878 MWh of behind-the-metre BESS, primarily in industrial (47%), residential (32%), and commercial (20%) sectors, with a 1% of off-grid systems (UNEF 2024). This rooftop capacity represents approximately 22% of the country's total 32 GW of installed solar PV, highlighting the growing but still secondary role of decentralised installations in Spain's overall solar deployment. This expansion was facilitated by Royal Decree 244/2019 (Real Decreto 244/2019 2019) which established a comprehensive framework for self-consumption installations, and further reinforced by Royal Decree-Law 23/2020 (Real Decreto-Ley 23/2020 2020), which introduced the legal recognition of renewable energy communities and streamlined administrative procedures to support decentralised energy initiatives. This decree established a comprehensive framework for deploying rooftop PV installations nationwide, streamlining procedures and requirements for installation, connection, and surplus energy compensation. Under RD 244/2019, a financial mechanism was introduced for energy exported to the grid, facilitating bill reductions tied to the electricity injected into the grid at the hourly wholesale price, with a maximum decrease in actual consumption. Moreover, the regulatory framework supports shared self-consumption installations, enabling multiple consumers to collectively benefit from a single renewable energy system.

Furthermore, Spain's commitment to renewable energy is exemplified by the National Integrated Energy and Climate Plan 2023–2030 (MITECO 2024), which sets ambitious targets for expanding renewable energies and reducing greenhouse gas emissions, also targeting decentralised RET. Aligned with directives from the European Union, this plan underscores Spain's dedication to sustainable energy policies at both domestic and industrial levels. Complementing regulatory measures are various financial incentives implemented to promote decentralised renewable energy systems, including feed-in tariffs, tax credits, grants, and subsidies. These incentives aim to stimulate investment in RET and foster the widespread adoption of distributed generation systems.

Spain's regulatory system also distinguishes between installations above and below 100 kW. Systems ≤ 100 kW qualify for simplified net billing. This structured approach has facilitated the scaling up of small and medium-sized RETs, supporting Spain's broader strategy for a resilient and distributed energy future.

Comparison between Colombia and Spain

Colombia and Spain both aim to expand decentralised renewable energy. However, their energy policy frameworks, institutional maturity, and socio-economic conditions differ. Spain's approach is shaped by its integration within the European Union, which provides a coherent regulatory structure, access to financial instruments, and a long-term vision aligned with climate targets. Conversely, Colombia has exhibited a lower level of implementation of decentralised renewable energies than Spain, with a high prominence of the private sector and limited state presence, reflecting a slower adoption rate and additional challenges. Colombia is still developing its regulatory and market architecture, with a greater emphasis on overcoming energy poverty and ensuring equitable access, particularly in rural and non-interconnected zones.

These differences justify the comparative focus of this study: Spain represents a more consolidated, policy-driven model of decentralised RET deployment, while Colombia shows the challenges faced by countries with greater systemic and infrastructural constraints in establishing enabling environments for decentralised RET. The factors influencing the promotion and development of decentralised renewable energies can vary significantly depending on each country's political, economic, technical, and social context. Therefore, specific DBs will likely differ in each case, reflecting the unique conditions and particular challenges each nation faces in transitioning towards a more sustainable and diversified energy system. Yet, both countries aim to increase RET adoption to advance climate and equity goals. Analysing them comparatively enables a deeper understanding of how context shapes drivers and barriers, and how policy responses must adapt accordingly.

Methods

This study proposes the identification of DBs for the Colombian case, and their comparison with the case of Spain analysed in a previous study (Aparisi-Cerdá et al. 2024). To achieve this, the method illustrated in Fig. 1 is proposed. The ANP is used to assess the importance of the DBs with expert knowledge (see section "Analytic network process methodology").

The first stage involves the preparation of the ANP models. This includes validating the initial list of identified DBs from the Spain case study with energy experts in the Colombian context and replicating the process carried out in the Spain case. The initial sets of identified DBs in the specific case analysis of Spain are presented to a group of energy experts from three sectors: industry, government, and academia. These experts adapted the DBs to the Colombian case.

The second stage consists of constructing and comparing the ANP models for both countries. ANP models for the DBs of the analysed technologies for Colombia are built based on the results from the previous stage. Finally, the models obtained for Colombia are compared with the models from the case of Spain.

The third stage involves solving the ANP models and obtaining prioritisations for the new Colombian case study. This phase concludes with the analysis of the results from both case studies.

Lastly, the fourth stage consists of the final assessment and comparison of the DBs for Colombia and Spain, including differences and implications and providing recommendations.

Definition of the models

The ANP has been used to evaluate the DBs' importance and interrelation for two RETs (solar PV and batteries). The ranking models are based on a network of criteria (DBs) and alternatives (types of RET) that influence each other. The DBs are derived from a previous SLR (Aparisi-Cerdá et al. 2024) and consultations with academic experts in each study country. Depending on their nature, DBs are clustered into four categories: technical, social, economic and institutional. This method captures the variety of DBs without impairing the model's ability to be used by experts or preventing comprehensive comparisons between its representative elements.

A total of eight models have been used, four models for both countries. Two models have been generated for the barriers identified in each country, one for PV and one

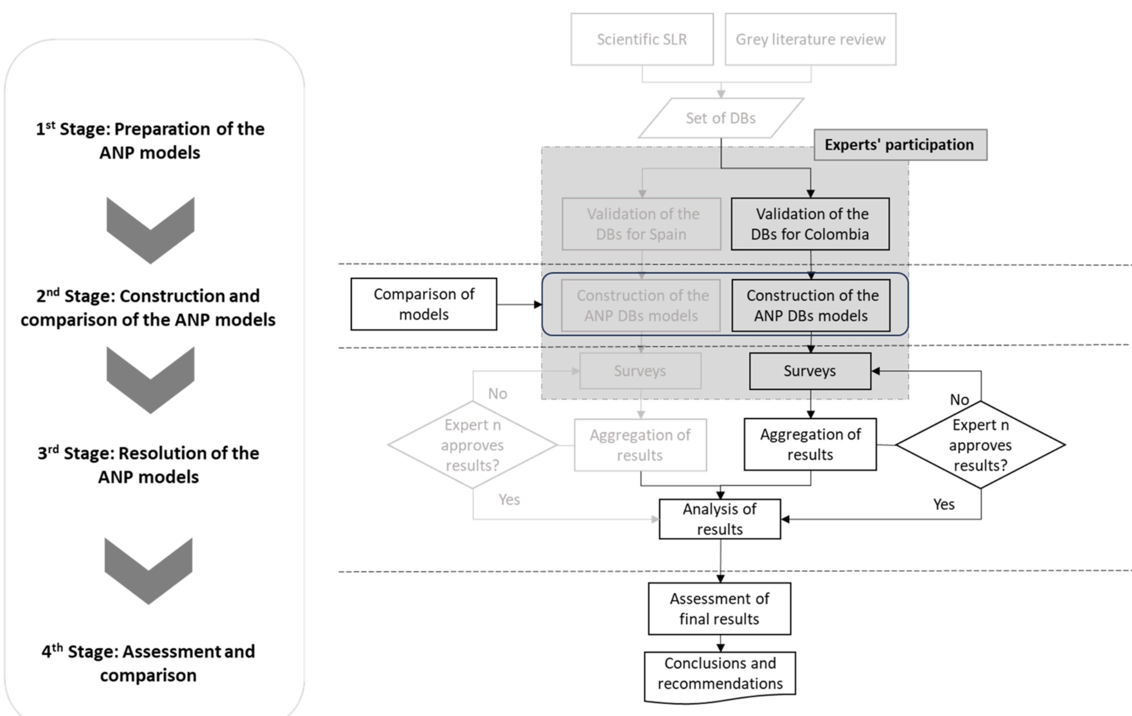


Fig. 1 Method. Adapted from [(Aparisi-Cerdá et al. 2024)]

for batteries, and likewise, for the drivers. The weights obtained by applying the ANP reflect the prioritisation of BDs for each technology. These weights indicate the relative importance of each barrier and driver for each of the two technologies.

In participatory approaches such as ANP, the quality and diversity of expert input is more critical than the size of the panel. Literature suggests that a group of 10–15 carefully selected participants is sufficient for robust MCDA applications (Saaty 2001). In this study, experts were chosen to ensure sectoral balance across academia, industry, and government, as well as experience with either residential or industrial RET contexts. To minimise potential selection bias, both countries applied the same criteria and stakeholder composition consistently, ensuring comparability and reducing the risk of disproportionate representation.

Although environmental sustainability is a key motivation behind renewable energy transitions, environmental factors were not identified by experts in either Spain or Colombia as direct drivers or barriers to adoption. This outcome reflects the context-sensitive nature of the ANP methodology, where prioritisation emerges from expert input rather than predefined criteria. The focus of the expert panels was primarily on operational, regulatory, economic, and social factors shaping adoption decisions, while environmental benefits were regarded as overarching goals rather than decision-making parameters.

Analytic network process methodology

DBs for the two types of technologies investigated are prioritised using a multi-criteria decision-making (MCDM) methodology (Belton and Stewart 2002), which is tailored for analysing intricate and uncertain scenarios, a focus of this study. The specific MCDM approach adopted in this research is the ANP introduced by Saaty (2004). ANP offers a structured framework for tackling decision-making or evaluation challenges by encompassing a cluster network comprising criteria (drivers or barriers) and alternatives (types of technology). Unlike many other MCDM techniques, ANP allows for flexible interrelationships among network components, facilitating the integration of feedback loops and interdependence both within and across clusters. This capability enables precise modelling of complex contexts and addresses the typical scenario of interdependence among elements, such as in the models of barriers or drivers to RET. ANP has found application in the renewable energy domain for decision-making in policies (Cannemi et al. 2014), participation in renewable energy initiatives (Gómez-Navarro and Ribó-Pérez 2018), prioritisation of renewable energy sources (Kabak and Dağdeviren 2014), or energy technologies for microgrids (Ribó-Pérez et al. 2020).

ANP's effectiveness stems from its application of a 1-to-9 ratio scale, simplifying the portrayal of diverse interactions among tangible and intangible criteria. These interactions are translated into weights or preferences, established through pairwise comparisons among elements within each level. The relative importance of elements concerning their controlling criteria is gauged using this scale (Saaty 2004).

The ANP method is applied in the following main steps:

(1) Identifying the components and network elements and their relationship.
(2) Conducting pairwise comparisons based on ratio scales.
(3) Incorporating resultant relative importance weights (eigenvectors) into the matrix (unweighted matrix).
(4) Performing pairwise comparisons on clusters.

The relevance of each element of the network is a non-dimensional value. Based on the questions made in a questionnaire to feed the method, ANP weighs the influence of the DB on the other DB and the technologies for both countries.

The expert prioritisation (pairwise comparisons) for Colombia was conducted through online sessions between March and August 2024. A total of ten experts from industry (5), government (3) and academia (2) participated. The responses were treated individually using Super Decisions software, and were then aggregated using the arithmetic mean, following standard ANP procedures, to obtain the group response.

Spearman rank correlation

Analysing compatibility among experts is crucial for understanding the degree of consensus or variability in their perspectives, which can directly impact the effectiveness of sectoral policies and strategies. A high level of compatibility suggests a shared vision among experts, facilitating the implementation of coordinated actions (Bedő and Ong 2016; Koike and Hofert 2024). Conversely, identifying areas of low compatibility highlights differences in priorities or approaches between sectors, indicating the need for further dialogue to align perspectives and develop more comprehensive and representative policies.

To measure compatibility between pairs of experts, the Spearman Rank Correlation Index (SRCI) was calculated by evaluating the alignment between the ranks of priority values assigned by each expert. Given two ranked vectors R_i and R_j, the SRCI is calculated as follows:

$$\mathrm{SRCI}_{ij} = 1 - \frac{\sum_{k=1}^{n} (R_{ik} - R_{jk})^2}{n(n^2 - 1)} \tag{1}$$

where R_{ik} and R_{jk} are the ranks of criterion k for experts i and j, and n is the number of criteria. The higher the value of SRCI, the more aligned the prioritisation vectors are.

Results

This section presents the results of the comparative analysis on the adoption of decentralised RETs in Spain and Colombia. Using the ANP, the study assesses and ranks the relative importance of various DBs influencing the adoption of RETs in each country. The analysis begins with a contextual comparison of the identified DBs, highlighting the main differences between the two national contexts. The following sections present the prioritisation of these DBs, examining their relative weight. Variations in prioritisation by technology type and expert profiles are also analysed. Finally, the compatibility of experts' views across sectors is assessed, providing a better understanding of consensus and divergence within and between the countries studied.

Comparison of models

After a review and validation with Colombian experts, it was confirmed that many DBs identified in the Spanish context remain relevant in Colombia. However, key differences emerged that reflect distinct contextual realities. These differences are summarised in Tables 1 and 2.

The removal of DBs related to collective self-consumption and community culture stems from the absence of relevant experiences in Colombia. Despite interest from both private and public sectors, shared production has not yet been established. While this aspect is acknowledged in the national development plan, such models have been initiated only by government-led efforts and remain at a very early stage. Additionally, the driver "transposition of European directives" was replaced by "regulatory developments" to reflect Colombia's ongoing regulatory evolution. Context-specific drivers such as "service supply failures", a response to frequent outages, and the transformation of “access to funding” into a barrier, “lack of funding”, reflect the impact of Colombia's infrastructural and financial context.

Among the barriers, "environmental conditions" was included, such as tropical humidity, high temperatures, and radiation hours, highlighting physical performance challenges that differ from those in Spain and are unpredictable compared to ideal factory conditions. Conversely, Spain’s "electricity tariff structure" was not considered a barrier in Colombia due to different systemic dynamics In Colombia, electricity tariff structures may not pose a significant barrier to adopting decentralised renewable technologies as in Europe, owing to broader systemic issues such as regulatory limitations, market constraints, and infrastructure challenges.

While most DBs remain consistent across contexts, these variations are essential to understanding how national

Table 1 Comparison of drivers

Spain		Colombia	
Id	Economic drivers	Id	Economic drivers
DE1	Fiscal and economic incentives	DE1	Fiscal and economic incentives
DE2	Access to sufficient funding	–	*It is a barrier*
DE3	Environmental charges	DE3	Environmental charges
DE4	Stabilisation of low energy prices	DE4	Stabilisation of low energy prices
Id	Institutional drivers	Id	Institutional drivers
DI1	Transposition of European directives	–	*Not applicable*
DI2	Political will	DI2	Political will
DI3	Market participation mechanisms	DI3	Market participation mechanisms
–	–	*DI4**	*Regulatory developments*
Id	Social drivers	Id	Social drivers
DS1	Clear, reliable and accessible information	DS1	Clear, reliable and accessible information
DS2	Awareness, education and training programmes	DS2	Awareness, education and training programmes
DS3	Adopter’s motivation	DS3	Adopter’s motivation
DS4	Community culture	–	*Not applicable*
Id	Technical drivers	Id	Technical drivers
DT1	Existing infrastructure	-	*It is a barrier, part of BT1*
DT2	Technological maturity	DT2	Technological maturity
DT3	Development of infrastructures and uses	DT3	Development of infrastructures and uses
–	–	*DT4**	*Service supply failures*

Table 2 Comparison of barriers

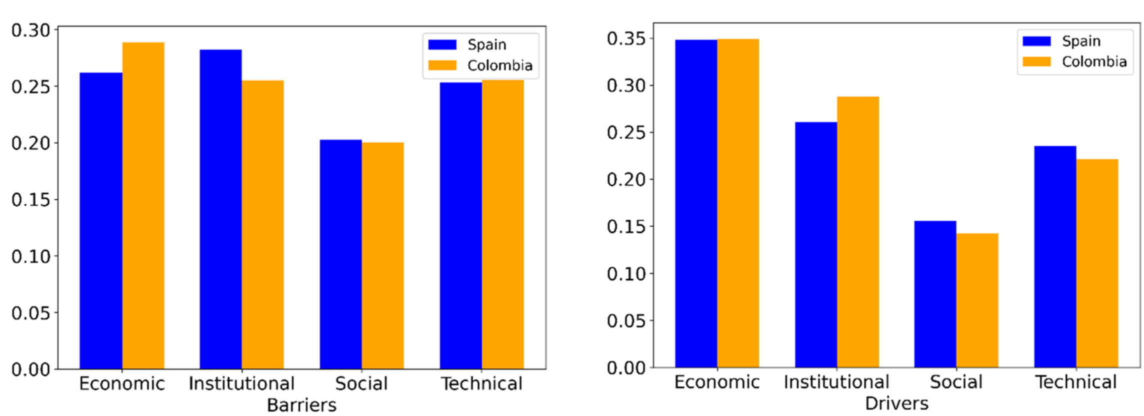
Spain		Colombia	
Id	Economic barriers	Id	Economic barriers
BE1	Investment cost (CAPEX)	BE1	Investment cost (CAPEX)
BE2	Electricity tariff structure	–	*Not applicable*
BE3	Economic profitability	BE3	Economic profitability
–	–	*BE4**	*Lack offunding*
Id	Institutional barriers	Id	Institutional barriers
BI1	Lack of technical definition and standardisation	BI1	Lack of technical definition and standardisation
BI2	Institutional inertia	BI2	Institutional inertia
BI3	Licensing	BI3	Licensing
Id	Social barriers	Id	Social barriers
BS1	Risk aversion	BS1	Risk aversion
BS2	Rejection of dependence on third parties	–	*Not applicable*
BS3	Lack of energy awareness	BS3	Lack of energy awareness
BS4	Lack of know-how	BS4	Lack of know-how
Id	Technical barriers	Id	Technical barriers
BT1	Space issues	BT1	Space issues
BT2	Techno-economic uncertainty	BT2	Techno-economic uncertainty
BT3	Technological complexity	BT3	Technological complexity
–	–	*BT4**	*Environmental conditions*

conditions shape adoption priorities. In the light of these observations, only solar PV and battery energy storage systems (BESS) were analysed in the Colombian case. In Spain, the analysis also included energy management technologies. The narrower technological focus in Colombia reflects the country's current priorities and practical deployment stage.

Prioritisation by cluster

While the individual DBs differ, comparing the economic, institutional, technical, and social clusters provides insights into the overarching structure of barriers and drivers in each country. Figure 2 represents each cluster's aggregated relative weight (arithmetic mean), reflecting its overall importance as prioritised by experts. The most marked difference appears in barriers: economic barriers dominate in Colombia, while institutional ones are more prominent in Spain. Technical and social barriers rank third and fourth in both countries, with comparable weights.

In terms of drivers (Fig. 2b), the order of priority is the same in both countries: economic first, followed by institutional, technical and finally social. The difference is that in Colombia, institutional drivers gain some weight in this hierarchy, while technical and social drivers lose some weight.



a) Barriers prioritisation

b) Drivers prioritisation

Fig. 2 Prioritisation of drivers and barriers (DBs) grouped by cluster

Economic factors play a pivotal role in Colombia's case; they are not only the main barrier but also the main driver. In Spain, where the current level of adoption and experience with these technologies is more extensive, economic factors remain the main drivers, but institutional factors are more limiting. This contrast illustrates each country's diverging challenges: Spain, with a more mature decentralised energy system and greater stakeholder experience with the regulatory limitations affecting services and business models linked to RETs, focuses on institutional optimisation. In contrast, Colombia's evolving framework brings economic and access-related barriers to the forefront.

Drivers proritisation

This section provides a detailed analysis of the key drivers in both countries, focussing on the prioritisation and weighting of each in shaping their respective economies. Figure 3 illustrates how these drivers are prioritised in Colombia and Spain, highlighting those that account for 60% of the total weight in each case.

When setting this 60% threshold, four drivers account for 60% of the total weight in Colombia, whereas in Spain, the top five drivers are more evenly distributed. This suggests a more concentrated reliance on a few critical drivers in Colombia and a broader base in Spain.

Both countries' primary common economic drivers are *Fiscal and Economic Incentives (DE1)* and *Stabilisation of Low Energy Prices (DE4)*. However, the relative weight of these differs significantly. While in Spain the weight is more distributed, in Colombia half of the total weight is concentrated in three drives: *Market Participation Mechanisms (DI3)*, *DE1*, and *DE4*. *DI3* plays a crucial role in Colombia but does not have the same level of importance in Spain. Completing the group of drivers that make up 60% in Colombia is *Service Supply Failures (DT4)**, a driver absent in Spain.

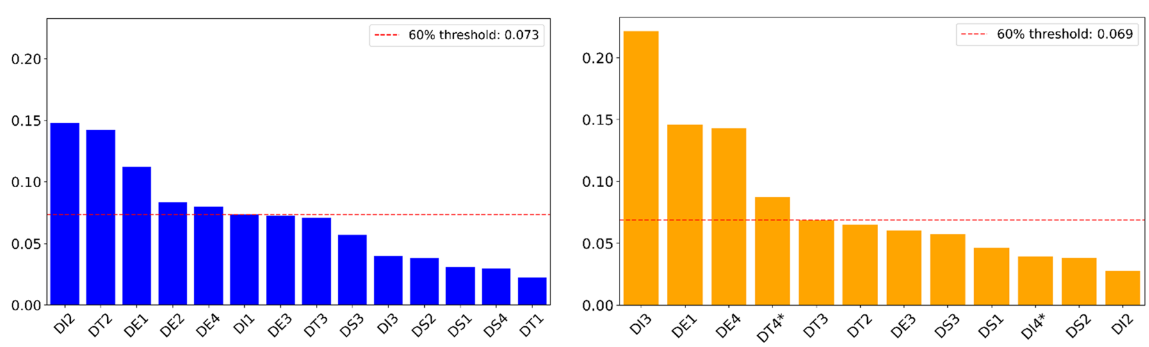
No significant differences were found between the two technologies. However, some of the differences are found for the main drivers. In Spain, batteries have a slight prevalence regarding the *Stabilisation of Low Energy Prices (DE4)* and PV regarding *Access to sufficient funding (DE2)*. In Colombia, the importance of *Fiscal and Economic Incentives (DE1)* is greater for PV than for batteries, and *Service Supply Failures (DT4)** is greater for batteries (Fig. 4).

In terms of expert perspectives, Colombia shows greater disparity between experts in terms of economic, social, technical and institutional drivers, including the drivers highlighted as the main ones (Fig. 5b). In Spain main drivers show a similar response regardless of the type of expert (Fig. 5a), however, there are some differences among some economic and social drivers.

Barriers prioritisation

Similar to the analysis of drivers, Fig. 6 shows the prioritisation of barriers, highlighting those that account for 60% of the total weight. In both cases, the barriers that account for 60% of the total weight are five. However, it can be observed that there is a more uniform distribution of weights in Spain and a more distinct distribution in Colombia, as observed for the drivers. Among these primary barriers, *Techno-economic Uncertainty (BT2)*, *Lack of Know-how (BS4)*, and *Lack of Technical Definition and Standardisation (BI1)* are common to both countries. However, the primary barrier in Colombia is *Lack of Funding (BE4*)*, while in Spain, *Access to Sufficient Funding (DE2)* is one of the main drivers. Additionally, one of the main barriers in Spain, *Electricity Tariff Structure (BE2)*, does not apply in the case of Colombia.

In the case of Spain, *the Lack of Technical Definition and Standardisation (BI1)* is slightly more relevant for batteries *Licensing (BI3)* for PV (Fig. 7). In the case of Colombia, the most appreciable difference between technologies is in the case of the main barrier, *Lack of Funding (BE4*)*.



a) Spain **b)** Colombia

Fig. 3 Prioritisation of drivers in both countries. Note: Definitions of each driver are provided Table 1

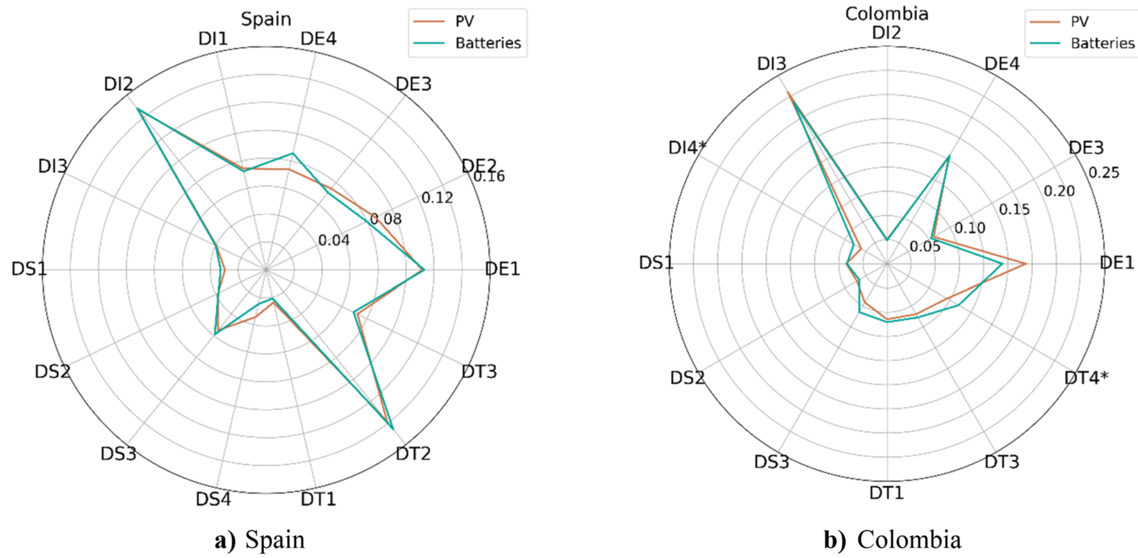


Fig. 4 Drivers' prioritisation by technology type

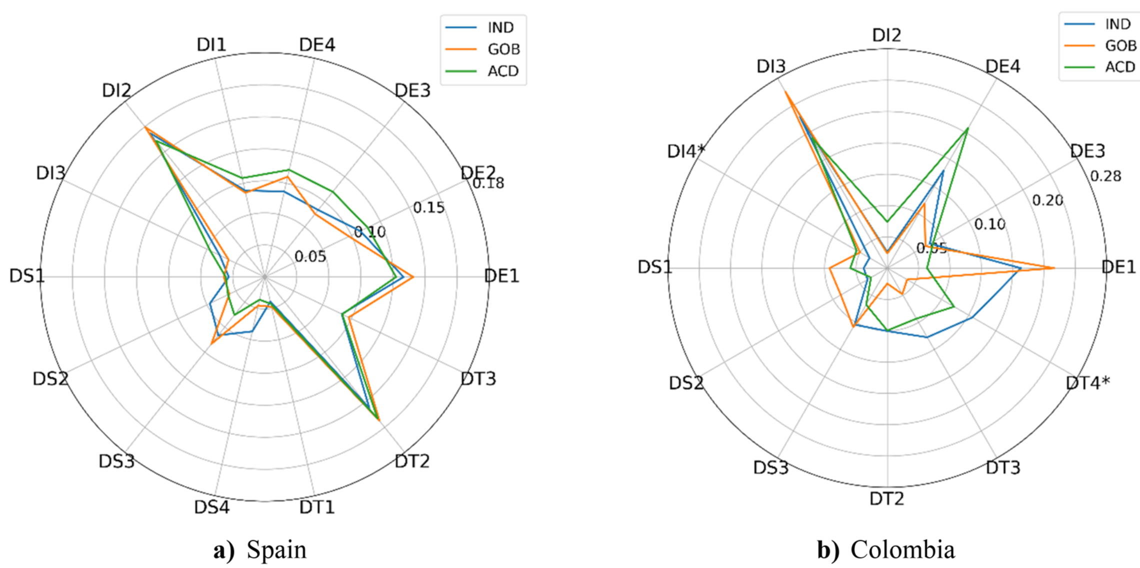


Fig. 5 Drivers' prioritisation by expert type

The analysis of expert prioritisation reveals a stronger alignment among industrial, academic, and governmental experts in Spain. In contrast, significant disparities are evident among experts in Colombia regarding some of the main barriers (BE4*, BT2, BS4, BE1) (Fig. 8).

Expert compatibility

The observed differences in prioritisation between experts are further analysed through an expert compatibility analysis using the Spearman correlation. The analysis reveals distinct patterns in expert perspectives on the DBs with varying degrees of intra- and inter-sector compatibility. Intra-sector refers to compatibility within the same type of experts, while inter-sector refers to alignment between two different types of experts.

For intra-sector compatibility on drivers, Spain shows stronger alignment across academia (0.84), government (0.85), and industry (0.67), with the government displaying the highest cohesion. In Colombia, academia also leads with a lower score (0.64), while industry shows moderate compatibility (0.58), and government shows the lowest (0.32).

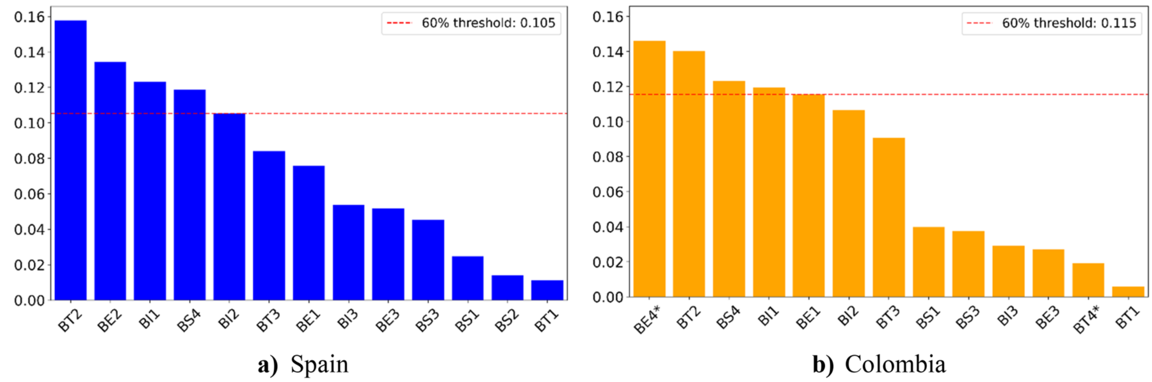


Fig. 6 Prioritisation of barriers in both countries. Note: Definitions of each driver are provided in Table 2

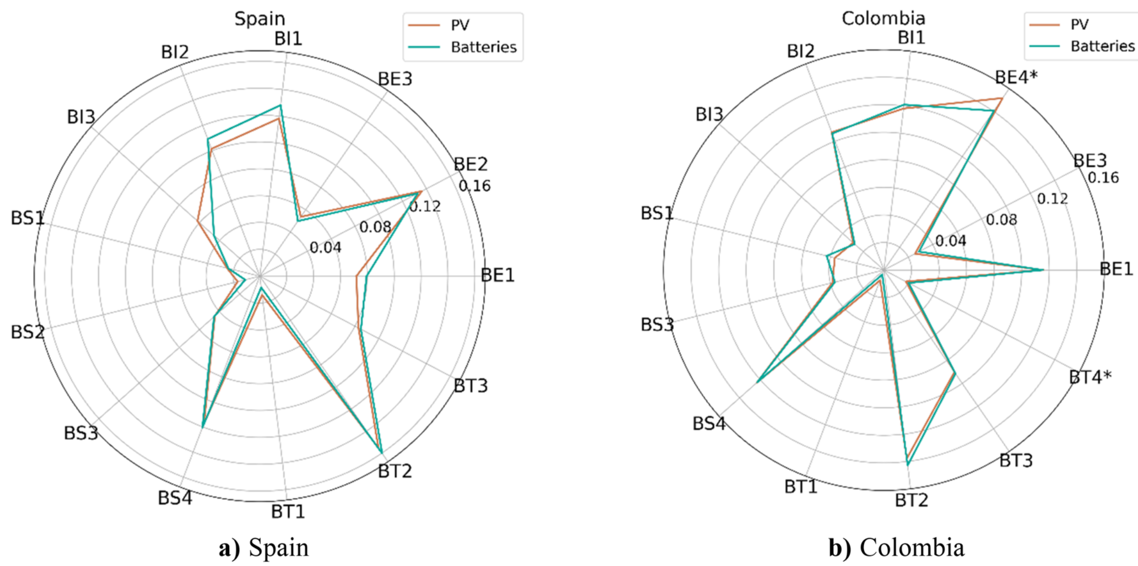


Fig. 7 Barriers' prioritisation by technology type

This suggests that Spanish government bodies have a more unified view on drivers of renewable energy than those in Colombia, where governmental perspectives appear more diverse.

Regarding barriers, both countries exhibit the highest intra-sector alignment within academia, with correlations of 0.91 in Spain and 0.92 in Colombia, reflecting strong academic consensus. Colombia shows slightly higher alignment within the industrial sector (0.84) than Spain (0.77), indicating a more unified industry perspective on barriers. Meanwhile, Spain's government experts show stronger alignment (0.88) than their Colombian counterparts (0.77).

In terms of inter-sector compatibility for drivers, Spain again shows greater alignment, especially between academia and government (0.80), followed by industry-government (0.73) and a lower alignment between industry and academia (0.61). In Colombia, inter-sector compatibility is generally lower, with moderate alignment between industry and academia (0.66), industry-government at 0.50, and the lowest between government and academia (0.48). This stronger alignment in Spain suggests a more cohesive research-policy approach to renewable energy. In comparison, the lower alignment in Colombia, particularly between government and academia, may indicate gaps between policy frameworks and research priorities.

For barriers, both countries display high inter-sector compatibility between industry and government, indicating alignment on regulatory and operational challenges. Spain's highest compatibility is between academia and government (0.87), followed by industry-government (0.84), with moderate alignment between academia and industry (0.79). In Colombia, the highest compatibility is between industry and academia (0.84), followed by industry-government (0.81), while government-academia alignment remains moderate

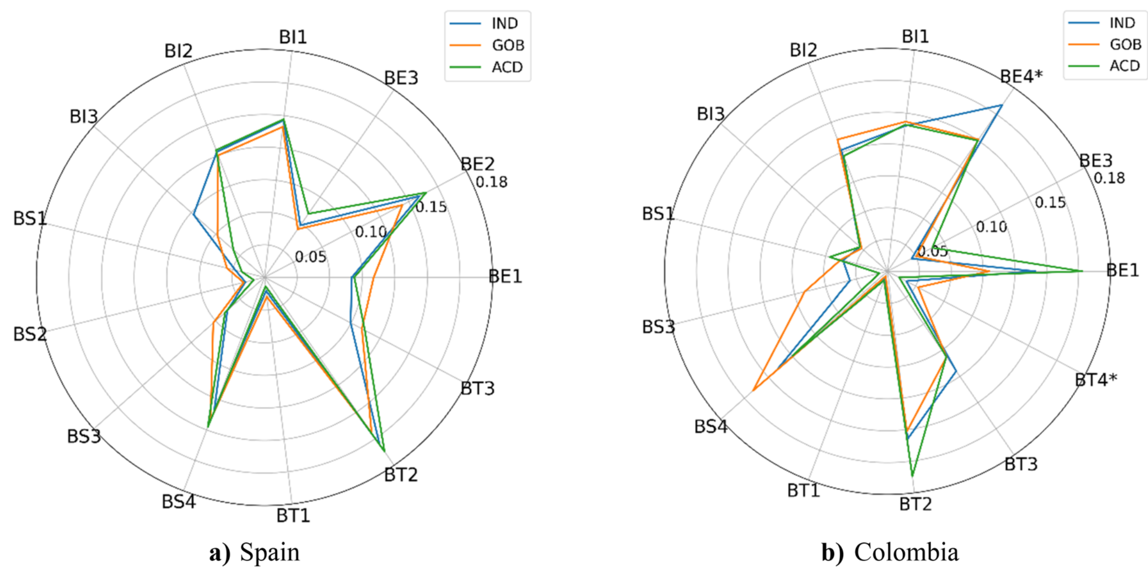


Fig. 8 Barriers' prioritisation by expert type

(0.73). Spain's higher academia-government compatibility may suggest a more effective collaboration in policy development informed by academic research.

Discussion

The results highlight how decentralised RET adoption is shaped by national regulatory maturity, economic stability, and institutional alignment. Our findings align with previous literature that highlights the importance of stable policy frameworks and financial incentives in fostering renewable energy transitions (Drago and Gatto 2022; O'Shaughnessy 2022). According to the results, Colombia's main drivers are market participation mechanisms, fiscal and economic incentives and stabilisation of low energy prices. In contrast, in Spain, there is greater emphasis on political will and technological maturity, although economic incentives remain a core driver in both contexts.

Regarding barriers, in Colombia, lack of funding and techno-economic uncertainty emerged as the most critical. These findings are consistent with challenges reported across Latin America, especially in rural isolated areas, where decentralised energy projects often face high investment costs, and technical or economic uncertainties related to system design and long-term feasibility. Studies from both isolated microgrids in Honduras (Ribó-Pérez et al. 2020) and decentralised energy systems in remote areas in the Brazilian Amazon (Mazzone 2019) reflect similar limitations in technical adequacy and long-term sustainability. In Spain, the most significant barriers were techno-economic uncertainty, the electricity tariff structure, and the lack of technical definition and standardisation.

This comparison highlights that in emerging decentralised energy markets like Colombia, regulatory promotion and market incentives are necessary but insufficient without addressing key economic and technical barriers. In contrast, mature markets such as Spain focus on refining policy and regulatory frameworks to enhance the efficiency, integration, and scaling up of distributed energy solutions.

In addition to these differences at the national level, the analysis reveals important contrasts in how stakeholder groups are aligned within each country. In Spain, the perspectives of experts from government, academia and industry are generally more consistent, especially on regulatory and technical issues. This convergence is reflected in high compatibility ratings across sectors, especially between government and academia, and suggests a shared understanding that may contribute to more stable and coordinated policy responses. Internal coherence among Spanish government experts also reinforces the impression of a consolidated institutional framework capable of responding effectively to decentralised energy challenges.

In contrast, Colombia shows a more fragmented pattern. Expert opinions are more spread out, especially within the government sector, which shows the lowest internal agreement of all groups. Moreover, the low agreement between government and academic experts suggests a potential disconnection between research and policymaking. While there is relatively greater compatibility between industry and academia, the lack of cohesion among public sector actors may hinder the formulation of consistent and well-informed strategies. This suggests that, beyond regulatory clarity and financial support, the degree of stakeholder alignment plays a key role in determining how energy transitions unfold.

Based on the priority factors and obstacles in each case, specific policy measures can be identified. In Colombia, policies should aim to mitigate structural economic barriers by improving access to finance and providing economic incentives to enhance social engagement. In addition, greater clarity on technical standards and accelerated implementation of the Community Energy Framework introduced by CREG in 2025 would help reduce uncertainty and broaden participation among citizens and local governments. Prioritising the electrification of remote rural areas through decentralised renewable energy solutions is also crucial, considering that the Non-Interconnected Zones cover more than half of the country's territory.

In Spain, policy refinements should focus on strengthening existing fiscal and economic incentives while addressing institutional bottlenecks. Beyond adjusting the electricity tariff structure, there is a need for a more robust commitment to integrating distributed energy systems into the national grid. This includes developing clear guidelines for their incorporation, enhancing grid planning to accommodate decentralised generation, and ensuring that regulatory frameworks facilitate the seamless integration of these technologies. Such measures would consolidate the maturity of these technologies and support the scaling up of distributed renewable energy solutions.

Although the results of this study are specific to Spain and Colombia, the comparison of two countries at very different stages of decentralised energy development provides a broader picture of how drivers and barriers change in institutional, economic, technical and social dimensions. The contrast between an established and an emerging context highlights the various challenges facing the adoption of decentralised RETs depending on market maturity and policy developments. Further research is needed to extend the comparison to a wider range of national contexts to strengthen the understanding of how local conditions influence decentralised energy transitions. In addition, future studies should consider how changes in technology costs, market dynamics and regulatory frameworks may reshape the relative importance of drivers and barriers over time. These results collectively answer the study's research questions by demonstrating how contextual differences, particularly in institutional maturity and economic capacity, and stakeholder alignment, influence the configuration and prioritisation of drivers and barriers. Furthermore, they underline the need for adaptive energy policy frameworks that are sensitive to the specific constraints and opportunities of each national context.

Conclusions

This study provides a comparative analysis of the DBs that influence the adoption of decentralised RETs in Spain and Colombia, highlighting the complexities and contextual specificities that shape renewable energy transitions. The need to adapt the DBs to reflect the realities of each country underlines how socio-economic and regulatory conditions influence the prioritisation of critical factors.

The findings reveal that, while economic incentives are key drivers in both countries, Colombia faces more structural barriers related to funding and techno-economic uncertainty, whereas Spain's challenges focus on refining regulatory and technical frameworks. The results underscore the strong influence of national institutional maturity and market conditions on the dynamics of decentralised RET deployment. Moreover, expert compatibility analysis revealed notable differences between the two countries, with a stronger alignment in Spain. The observed disparities in Colombia suggest that aligning expert perspectives could enhance the development and implementation of renewable energy policies, particularly in areas where accessibility and variability undermine a unified national strategy.

The findings highlight the importance of tailoring renewable energy strategies to the specific contexts of each country. Policy recommendations include the need for Colombia to strengthen access to financing, promote regulatory clarity, and foster cross-sector coordination to reduce adoption barriers. In Spain, policy efforts should focus on improving tariff structures, standardising technical procedures, and maintaining incentive schemes to sustain the expansion of decentralised RETs.

While based on two specific national contexts, this comparative analysis offers insights that may inform energy transition strategies in other settings. However, the findings are context-specific and may not be directly generalisable to countries with different institutional or socio-economic conditions. Future studies should continue to adapt and test this framework across diverse regulatory and market environments. In addition, it will be important to monitor how technological advances, market developments, and policy changes reshape the relevance of drivers and barriers over time.

Appendix

Below the Spearman correlation calculations, where Expert codes (e.g. acad1, gob1, ind1) identify individual respondents by sector—academia (acad), government (gob), and industry (ind)—with the number indicating their sequence within each group (e.g. acad1 = first academic expert) (Tables 3, 4, 5, 6).

Table 3 Spearman correlation barriers Spain

	acad1	gob1	acad2	acad3	ind1	gob2	gob3	ind2	gob4	ind3	gob5	acad4	gob6	ind4
acad1	1.000	0.967	0.962	0.791	0.846	0.945	0.819	0.945	0.813	0.885	0.780	0.864	0.820	0.652
gob1		1.000	0.984	0.802	0.890	0.984	0.824	0.929	0.813	0.885	0.747	0.886	0.842	0.762
acad2			1.000	0.841	0.879	0.973	0.830	0.940	0.830	0.879	0.731	0.880	0.842	0.726
acad3				1.000	0.835	0.764	0.940	0.896	0.973	0.874	0.676	0.806	0.773	0.740
ind1					1.000	0.868	0.824	0.901	0.835	0.786	0.687	0.845	0.828	0.759
gob2						1.000	0.780	0.912	0.769	0.852	0.731	0.894	0.845	0.737
gob3							1.000	0.868	0.929	0.890	0.725	0.809	0.770	0.773
ind2								1.000	0.923	0.907	0.786	0.911	0.872	0.699
gob4									1.000	0.901	0.670	0.817	0.784	0.787
ind3										1.000	0.863	0.911	0.905	0.773
gob5											1.000	0.864	0.880	0.459
acad4												1.000	0.983	0.749
gob6													1.000	0.733
ind4														1.000

Table 4 Spearman correlation drivers Spain

	acad1	gob1	acad2	acad3	ind1	gob2	gob3	ind2	gob4	ind3	gob5	acad4	gob6	ind4
acad1	1.000	0.898	0.855	0.877	0.200	0.903	0.837	0.749	0.851	0.833	0.873	0.859	0.499	0.631
gob1		1.000	0.957	0.928	0.288	0.898	0.854	0.724	0.838	0.812	0.836	0.840	0.664	0.673
acad2			1.000	0.873	0.367	0.824	0.758	0.587	0.723	0.697	0.815	0.776	0.648	0.736
acad3				1.000	0.284	0.903	0.873	0.758	0.881	0.829	0.802	0.886	0.591	0.710
ind1					1.000	0.196	0.191	0.314	0.073	0.349	0.266	0.429	0.442	0.130
gob2						1.000	0.930	0.811	0.886	0.868	0.837	0.859	0.618	0.692
gob3							1.000	0.802	0.895	0.820	0.749	0.824	0.596	0.569
ind2								1.000	0.895	0.982	0.802	0.877	0.776	0.411
gob4									1.000	0.908	0.820	0.868	0.670	0.596
ind3										1.000	0.851	0.912	0.776	0.503
gob5											1.000	0.925	0.657	0.508
acad4												1.000	0.640	0.464
gob6													1.000	0.521
ind4														1.000

Table 5 Spearman correlation barriers Colombia

	IND1	IND2	IND3	IND4	IND5	GOB1	GOB2	GOB3	ACD1	ACD2
IND1	1.000	0.758	0.808	0.819	0.830	0.879	0.846	0.685	0.770	0.692
IND2		1.000	0.824	0.824	0.786	0.896	0.912	0.737	0.801	0.791
IND3			1.000	0.934	0.912	0.874	0.901	0.713	0.856	0.912
IND4				1.000	0.934	0.885	0.835	0.586	0.949	0.907
IND5					1.000	0.797	0.841	0.696	0.883	0.846
GOB1						1.000	0.863	0.713	0.856	0.819
GOB2							1.000	0.746	0.754	0.808
GOB3								1.000	0.529	0.594
ACD1									1.000	0.919
ACD2										1.000

Table 6 Spearman correlation drivers Colombia

	IND1	IND2	IND3	IND4	IND5	GOB1	GOB2	GOB3	ACD1	ACD2
IND1	1.000	0.671	0.476	0.203	0.629	-0.007	0.923	0.657	-0.021	0.650
IND2		1.000	0.741	-0.126	0.734	-0.175	0.594	0.622	0.357	0.762
IND3			1.000	-0.147	0.895	-0.189	0.483	0.301	0.406	0.860
IND4				1.000	0.161	0.252	0.371	0.245	0.042	0.014
IND5					1.000	-0.021	0.601	0.406	0.266	0.776
GOB1						1.000	0.105	0.140	0.161	-0.385
GOB2							1.000	0.636	0.126	0.629
GOB3								1.000	-0.056	0.448
ACD1									1.000	0.343
ACD2										1.000

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Authors contributions Isabel Aparisi-Cerdá: Writing—original draft, Methodology, Visualisation, Data Curation. David Ribó-Pérez: Conceptualization, Methodology, Writing—review and editing. Hannia Gonzalez-Urango: Software, Data curation, Methodology, Writing—review and editing. Iván Ligardo-Herrera: Software, Data curation, Methodology, Writing—review and editing. Mónica García-Melón: Methodology, Supervision, Writing—review and editing.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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