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Assessment of Urban Wind Potential and the Stakeholders Involved in Energy Decision-Making

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Abstract: Urban wind energy has emerged as an attractive source of distributed generation in cities to achieve sustainable development goals. The advancement in technologies for the use of urban wind energy has offered an alternative for the decarbonization of cities and the energy transition. The objectives of this work are (1) to identify the potential of wind energy through numerical weather prediction (NWP) data tools and (2) to identify the roles and responsibilities of the stakeholders involved in the decision-making process. A methodology was developed in two phases and applied to a case study in the Dominican Republic. The first phase consisted of estimating the wind energy potential for the 32 provinces at a height of 10 m using open access NWP tools provided by NASA. In the second phase, 28 stakeholders were identified through snowball sampling. The Responsible, Accountable, Consulted, and Informed (RACI) matrix tool was applied to identify the roles of the 28 institutions addressed at the country level as relevant in the decision-making process for the energy sector. The annual average wind speed and energy potential for each province were determined. It was found that 24 provinces have poor potentials, below <4.5 m/s. In the northwest and east is where there is the greatest potential, between 4.83 and 6.63 m/s. The population density was established, and it was observed that the provinces with greater potential are less densely populated. Through 59 interviews, 28 institutions were identified and evaluated due to their relevance in decision making for the implementation of energy projects. According to the RACI matrix, the Ministry of Energy and Mines has been categorized as "A", electricity distribution companies as "R", energy associations and universities as "C", and educational and justice institutions as "I".

Keywords: urban wind energy; renewable energy; RACI matrix; decision making; small wind turbines; Dominican Republic

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1. Introduction

Decarbonization is a route to sustainable development that has been adopted by 196 countries to achieve stability from global warming. The intention is to reduce greenhouse gas emissions through the implementation of renewable energy solutions in the main economic sectors, and to achieve the planned decarbonization targets for 2030, 2040 and 2050. This objective is to achieve the goal of an average global warming of 2 °C in accordance with the agreements adopted by the United Nations at the Paris conference in 2015, which implies net zero emissions for some countries by 2050 [1]. This achievement is based on promoting energy generation with solar, wind and hydraulic energy, and antagonistically, completing the phase-out of coal- and gas-fired energy generation and the development of carbon-capture technology [2].

Other macroeconomic variables that may affect global sustainability are caused by force majeure events. The recent civil conflict between Russia and Ukraine has influenced the volatility of commodities and has included a geopolitical risk, mainly in Europe [3]. The conflict has caused an increase in fundamental commodities for the production of fossil energy and, at the same time, has driven European countries to accelerate decarbonization [4,5]. The sustainable development goals have imposed the paradigm of being able to live with the limits of the resources of the planet, and at the same time as the existing asymmetry in countries, such as the economic development of each one, the inequality of available resources, the distribution of the wealth, and the use of natural resources [6]. Energy is a pillar of the sustainable development goals (SDG), such as SDG7, which purpose is to ensure access to affordable, reliable, and sustainable energy services by 2030.

In the last decade, solar photovoltaic and wind energy have shown a considerable drop in prices, which has allowed these technologies to compete with traditional generation sources, where in the last 5 years on average it has fallen by 8% and 4%, for utility-scale solar power and onshore wind, respectively [7]. According to the renewable energy report from the International Renewable Energy Agency (IRENA), the power generation cost in 2022, on a weighted average, fell by 4% between 2021 and 2022, which corresponds to 3% and 5% for solar photovoltaic and wind energy, respectively [8].

It is essential to adopt decision-making tools to identify hidden factors that must be overcome for the adequate implementation of distributed technologies in urban environments to support the energy transition [9]. This energy transition is aimed at changing to a low-carbon energy system. Therefore, the development and implementation of renewable energy technologies, grid flexibility and energy storage, and the promotion of decentralized energy solutions, are required [10].

Cities are transforming towards the concept of Smart Cities in order to shape energy profiles, energy efficiency and infrastructure through digitalization and artificial intelligence, aiming for low-carbon energy-supply systems [11,12]. Urban wind energy has grown considerably in the last decade. In 2021, 40 MW of small wind turbines (SWTs) were installed in urban locations [13]. There is great potential in cities that can be exploited through SWTs integrated into buildings [14]. However, careful consideration should be given to the conditions of the orography and the obstacles to make a good evaluation about the resource's potential, which considerably influences the profitability of the project [15]. A trend with the keyword "urban wind energy" in the Lens database returned 5299 keywords, according to a bibliometric analysis of 8092 research works between 2020 and 2023 [16]. Figure 1 shows the keywords with a co-occurrence greater than 10, where 153 keywords were grouped through the software tool for constructing and visualizing bibliometric networks, coloured according to the most recent ones [17], where the most prominent were humans, economic development, environmental monitoring, China, air pollutants, cities, renewable energy, urbanization and wind. This indicates that this is a recent hot topic.

Urban areas are responsible for up to 70% of GHG emissions due to high economic development and population density [18]; urban wind energy can be a clean, safe and environmentally sustainable alternative to take advantage of this resource in cities [19]. The use of urban wind energy can be carried out through SWTs being integrated into existing buildings, in surrounding areas or being considered in the design of future architectural structures [20]. In response to the growing demand in cities, building-integrated turbines can be a sustainable and strategic solution to reduce the carbon footprint of buildings [21].

In dense urban environments, wind flow may be accelerated due to the geometries of buildings at certain heights; therefore, the kinetic energy of the flow can be captured through SWTs [22]. The wind flow pattern through SWTs on the roofs of buildings will depend on the shape of their roofs (rectangular, prismatic or conical, etc.) and their heights [23]. In this direction, the fundamental positioning of SWTs on the buildings, considering their morphology and the surrounding area, becomes relevant [22,24].

In the literature, there are few studies that address the identification of key actors and their roles for decision making to promote urban wind energy. SWTs in the urban environment can contribute to the mitigation of the use of polluting energy sources. However, it is a technology that can bring conflicts with the environment, such as noise generation, visual distortion, compromising the integrity of physical structures and the safety of people, if not incorporated in a professional manner. Therefore, it is necessary to identify key actors, e.g., institutions, which can develop regulations or conditions that allow the proliferation of this technology in urban areas. The most recent and comprehensive methodologies identified in this research are discussed below.

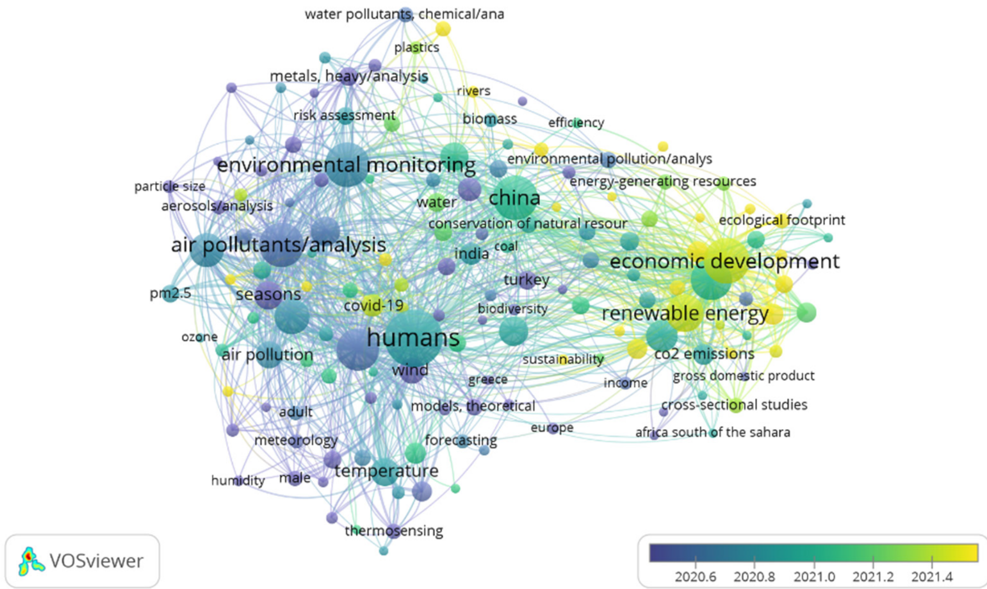

Figure 1. Top-10 co-occurrence keywords from the bibliometric analysis "urban wind energy".

Rezaeiha et al. [20] presented a methodology for wind energy assessment in the Netherlands. The authors determined an annual potential of 150.1 GWh in the 12 largest cities of the Netherlands, through the characterisation of existing buildings, urban wind analysis, SWT selection and annual energy production estimation. Wilke et al. [25] presented a methodology to determine how much urban wind energy can be produced through buildings, the equivalent CO_2 emissions that would be avoided, and the cost-effectiveness of a roof-mounted SWT in Berlin, Germany. The results indicate that approximately 5% of the electricity demands of households in Berlin can be covered. Furthermore, they indicated that to improve the performance of the distributed energy system, it could be complemented with other systems, such as solar photovoltaics. Gil-García et al. [26] carried out a study of urban wind potential in Spain. The authors presented a very detailed methodology consisting of site selection, wind potential study, annual energy estimation and economic and environmental analysis. The authors used NWP and GIS to carry out this study. Also, this research recommended the hybridisation of wind–solar systems for supply complementarity. According to the authors, more than 68,000 kWh/y can be produced, with a possible payback period of less than six years. Zagubień and Wolniewicz [23] presented a study of the energy efficiency of SWTs in four Polish cities. The authors evaluated the output of two vertical-axis wind turbines through the classification of five analysis zones for wind energy potential from 2 m/s to >6 m/s. The authors determined the annual energy and economic profitability for each zone. Also, they argue that for each urban zone, a minimum amount of annual energy produced is required for the profitability of the project, which must be determined for each specific zone.

Vallejo-Díaz et al. [27] estimated the urban wind energy potential in the two densely populated cities of the Dominican Republic. The authors complemented previous methodologies with the integration of energy resilience analysis for destroyed energy systems. The Dominican Republic is a tropical country and is exposed to tropical storms and hurricanes every 2–3 years, as is the case of Malaysia [28]. The authors have contributed to strengthening the existing methodologies so far, as a massive deployment of SWTs in tropical cities needs to predict, withstand, and recover from adverse weather events. So far, the methodologies presented have only focused on technical aspects of urban wind energy assessment. They have neglected the ecosystem of actors and the responsibility of those involved in the implementation of public policies and the development of energy projects. In this regard, Vallejo Díaz et al. [29] recently presented a hybrid Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analytic Hierarchy Process (AHP) analysis to determine the key factors influencing the proliferation of urban wind energy and the relevance of these factors. The authors applied the methodology to a case study from the Dominican Republic. However, previous studies have not considered the roles of key institutions that influence the decision-making process for the implementation of this technology. In that sense, this research seeks to integrate decision-making tools into existing methodologies for the characterisation of urban wind potential with the purpose of identifying the key roles of stakeholders to encourage the study, analysis, and possible use of this technology.

The objective of this research is divided into two phases; the first consists of identifying the urban potential of wind energy at the national level through free-access numerical weather prediction (NWP) data tools such as geographic information systems (GISs) provided by NASA's Prediction Of Worldwide Energy Resource (POWER) meteorological datasets [30]. In the second phase, a diagnosis through the Responsible, Accountable, Consulted, and Informed (RACI) matrix [31] is performed. This tool is applied to determine the roles of institutions (public, private, NGOs, associations and universities, etc.) in the development and promotion of the use of these types of technologies.

Decision-makers are defined by the International Atomic Energy Agency as those who identify problems that require a solution and select alternative options derived from decision-supporting studies, taking into account their values and priorities as well as the political and social environment in which they operate [32]. Nevertheless, given the interdependencies among sectors, and the complexity of considering social and environmental repercussions, decision-makers must look for comprehensive solutions that reflect the interests of a larger variety of stakeholders [33]. Given the unpredictability inherent in human conduct, decision-makers must exercise caution [34]. The fact that energy service infrastructure is long-lived and usually built to last decades emphasizes the importance of making the right decisions. Stakeholders are critical to any planning or decision-making process, as demonstrated by communicative planning and stakeholder engagement [35].

In the Dominican Republic, the electricity sector is geared towards meeting market demands; however, decisions come from the supply side and are regulated by the government. Currently, the energy supply is below demand, and it is the government institutions that are responsible for providing solutions, so their role should be perfectly defined. Stakeholders in the energy sector work at various levels of the power hierarchy and face competing interests. As a result, multiple stakeholders will view the issue in different ways, and each decision-maker's interpretation of the "best" solution will vary based on how they perceive risks and uncertainties [36]. The process of identifying and involving stakeholders is difficult, and the results can significantly affect how well a project turns out. This is especially more important when the project involves implementing sustainable technologies. Accordingly, decision-making models, techniques, and tools for mapping stakeholder decision making have been examined more closely [37]. The experience of this kind of analysis performed in other contexts has been considered [38–40]. Several of these are covered in the following section.

This article is structured as follows: Section 2 presents the proposed method approach for each phase, where the potential of urban wind energy is identified as a first step, and then qualitative and quantitative analyses are established through interviews, snowball sampling and surveys. Section 3 presents the results and a discussion of these through the application of the methodology to the case study of the Dominican Republic. Finally, Section 4 presents the conclusions.

2. Materials and Methods

This section is divided into two phases; the first presents an evaluation of the wind potential in the Dominican Republic through free-access datasets from numerical climate prediction [29,41]. In the second phase, previous methodologies are complemented with the RACI matrix tool to identify the responsible actors and their roles in order to take action or strategies for the proliferation of the use of urban wind energy [31].

Several methodologies have been presented for the comprehensive evaluation of urban wind energy potential. Basically, the methodologies include the stages of selection and characterization of the study area, the evaluation of the wind resource through various methods, the selection of the most appropriate wind turbine, the estimation of annual energy production, an economic estimation, an environmental impact evaluation and the evaluation of resilience [26,27,42]. Recently, tools for strategic planning have been included in existing methodologies, such as the SOWT-AHP analysis, to identify internal and external and positive and negative factors that can be included in the dissemination and use of this type of distributed technology [29].

Figure 2 presents the methodology proposed in this research, composed of two main phases; first, the evaluation of the potential of urban wind energy, and second, the identification of the key actors for decision making in the implementation of the technology and its use in urban environments.

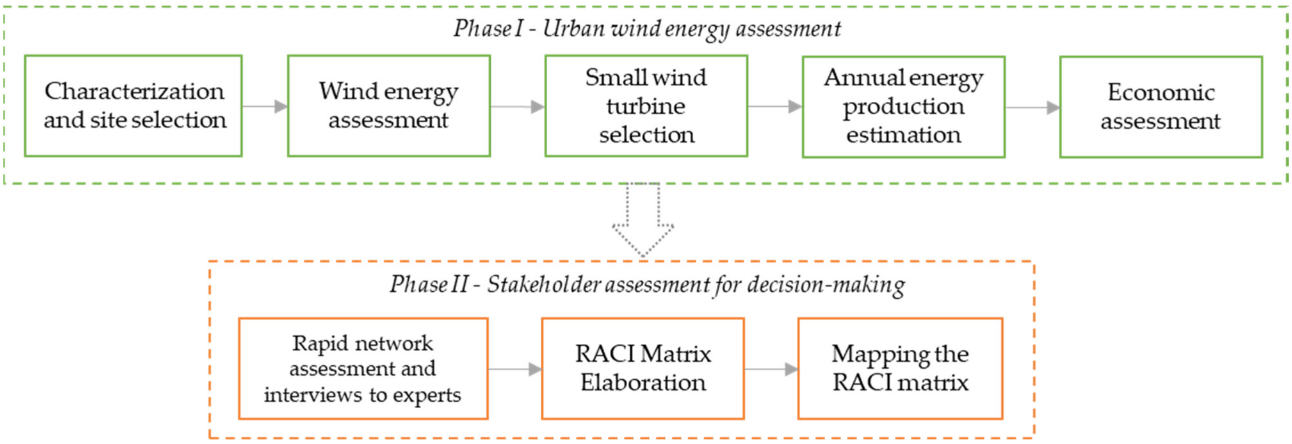

Figure 2. Framework of urban wind energy assessment and RACI analysis.

A detailed description of each phase presented in Figure 2 is broken down below.

2.1. Phase 1—An Analysis of Urban Wind Energy

- Site characterization and selection

The selection and characterization of the study area is an important part of starting the estimation of energy potential. Free-access datasets can be used, such as GIS, that contain meteorological information, such as NWP [43]. Usually, these applications provide meteorological parameters, such as wind speed and direction, temperature, barometric pressure, relative humidity, etc., at 10, 50, 100 and 150 m heights above the surface, and contain a seasonal variation during the year [44]. This approach, with mesoscale resolution, is important for identifying potential areas with greater wind energy rapidly and economically [26]. Recently, in Serbia, 16 potential locations for the production of half of the demand with wind energy were determined through a wind energy potential characterization program utilizing GIS data. The favourable speed was between 4.9 and 5.8 m/s, where the eastern plains and the western mountains showed better power [45]. On the other hand, as this research is focused on urban locations and not rural ones, the most favourable areas must be identified combined with those with greater urban development. Free-access tools such as [46] allow for discretizing the number of buildings by their heights in cities and, therefore, estimating the space available above the roofs of buildings for the use of wind energy [25].

This proposed methodology will be applied to a case study in the Dominican Republic. Therefore, some geographical and climatological details follow. The Dominican Republic is a Caribbean country, located 18°44′ N and −70°45′ W, with an area of 48,670 km^2. It owns the eastern two-thirds of the island of Hispaniola, between the Caribbean Sea and the North Atlantic Ocean, east of Haiti [47]. It has a humid tropical climate with an average annual temperature of 25.6 °C and an annual rainfall of 2167 mm [48]. The warmest month is June, and the coldest month is January. The average annual relative humidity is 80% [49].

- Wind energy analysis

For the analysis of wind energy, several methods are used for prospecting and analysing the resource. We assessed both the most used to the least utilized methods [27], including on-site measurement [50,51], with a spatial and temporary resolution in accordance with the guidelines in the IEC [52]. Followed by numerical climate prediction (NWP), these tools are widely used to relate meteorological variables with geographic maps that are displayed through the geographic information system (GIS), allowing for easy and expeditious use in obtaining the potential of the desired renewable resource [53]; however, this technique typically overestimates the wind because it does not consider turbulence and terrain morphology [54].

NASA climate and NWP data are good bases for an overall analysis. This typically involves several steps, including data acquisition, data pre-processing, analysis, and visualization. Data acquisition implies identifying the specific NASA datasets needed for the analysis and to follow the instructions to download the desired datasets in the required format. Data pre-processing is required to define the specific dataset and analysis objectives, and this allows us to identify and extract relevant variables, subsets of specific regions or time periods, and to perform quality control checks. In this stage, the necessary data processing are applied, such as unit conversions, spatial interpolation, temporal aggregation, or averaging, to prepare the data for analysis. In the data analysis process, various approaches depending on the research goals can be performed. This may include statistical analysis, machine learning, pattern recognition, or modelling. Finally, the visualization process should be carried out. This consists of visualizing the processed data and analysis results to gain insights and communicate findings effectively: for example, the wind resource maps for a region of interest for certain period.

Another technique is CFD simulation, which is used in order to obtain a more precise spatial resolution and study the behaviour of the wind flow in the area of interest. Normally, this allows to study the phenomenon on the scale of a few meters around the SWTs [55]. From the morphological approach, the NWP, on-site measurement and CFD simulation, allow the study of the resource from the regional, neighbourhood and block or street scale, respectively [56]. Other less common methods are the wind tunnel and analytical methods.

The wind tunnel provides interesting information about the wind flow that may not be obtained in a numerical simulation; however, it is more expensive and depends greatly on the homogeneity of the scale model being tested [57,58]. On the other hand, analytical methods have reported results that exceed certain physical limits because they do not adequately take into account some parameters, such as vegetation and terrain orography [59,60]. To obtain an adequate evaluation of the wind, two or three of the previously listed methods must be combined to validate the results of one. This is followed by the appropriate selection of the small wind turbine and the estimation of annual energy production, which influences the profitability indicators of the project.

- The Selection of small wind turbines

Small wind turbines (SWTs) integrated into buildings and peri-urban environments are a novel solution for power generation that has been gaining ground in recent years due to their architectural improvements and structural designs, which allow them to be aesthetically integrated into cities [61,62]. The most suitable SWTs depend on factors such as the cut-in wind speed, the flexibility of its installation and operation, and the aesthetic integration into urban environment [63]. According to the IEC standard, SWTs have a capacity of $\leq$50 kW and a rotor swept area of $\leq$200 m^2 [52]. According to the orientation of the axis, there are horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs are used for environments where the wind flows mostly laminarly and has low turbulence, since these turbines must be rotating to be located perpendicularly to the wind flow [64]. However, VAWTs are more appropriate for urban environments because they have better aerodynamic performance in high-turbulent and low-speed locations due to the unidirectionality of the rotor [65]. In addition, multiple investigations have been presented on the hybridization of VAWTs rotors to improve energy capture over a wide speed spectrum through the combination of drag force and lift [66].

- Annual energy production estimation

To estimate the annual energy production (AEP), the probability at a given wind speed is determined, and this is multiplied by the power that the SWTs will produce at that speed. Besides from the frequency probability, it depends on the cubed value of the average wind speed [67]. For this reason, it is vital to perform a good estimate of wind speed, as robust spatial and temporal details are needed for an adequate feasibility evaluation. Rezaeiha et al. [20,24] present the process for evaluating the AEP, which will be adopted in this work.

- Economic evaluation

To have a vision of the feasibility of a project, the economic component is crucial. The levelized cost of electricity (LCOE) consists of the discount to the present value of the entire cost of generation energy (capital cost, operation & maintenance cost, etc.), divided by the energy production for that same period, with previously determined financial parameters, such as interest rate and years [25,68]. Vallejo et al. [41] have analysed the cost of SWTs integrated into high-rise building in the capital of the Dominican Republic, where they have reported a LCOE from 0.4794 to 0.1419 USD/kWh for heights of 40 to 150 m, respectively. These costs are competitive because of the conditions of that wholesale electricity market.

As mentioned above, these five steps for the evaluation of urban wind energy have been well presented in the research presented by [20,26,27,42]. The intention of this subsection is to provide concise context about each step of this first phase, and to complement it with the analytical part of the research outlined above.

2.2. Phase 2—Stakeholder Analysis through RACI Matrix

Stakeholder analysis tools are crucial in the energy sector for understanding and managing the interests, concerns, and influences of various stakeholders involved in energy projects. Stakeholder analysis tools serve the following purposes: (a) to identify decision-makers; (b) to comprehend the various stakeholders' roles; and (c) to assist in providing information on decision-making processes, power dynamics, and stakeholder interests [69,70].

An approach for the quantitative analysis of the relationships between actors is stakeholder analysis, which involves understanding stakeholders with various degrees of expertise and priorities. Stakeholder analysis can be used to improve the transparency and equity of decision making in development projects by gaining an inventory of those who would be involved in decision-making, assessing their significance based on their level of influence and interest in a specific outcome, mapping the relationships between the actors, and determining their potential for forming alliances [71]. In the energy sector, stakeholders can include government agencies, regulatory entities, energy companies, local communities, environmental organizations, and consumers. Each stakeholder group may have different priorities, expectations, and potential impacts on energy projects.

In the context of the energy sector, stakeholder analysis has been used for a variety of applications, such as an analysis of Dutch stakeholder views on deep geothermal energy [72], an analysis of diesel tax reform in Spain [73], an analysis for the use of marginal land for biomass production in Denmark [74], an analysis of China's energy conservation campaign [75], and others. It has ranged from societal dialogue, politically viable energy transition, and governmental policymaking processes for the optimal environmental use of the land to achieve multifunctional benefits. Stakeholder analysis falls into one of two categories: either a top-down "analytical categorization" or a bottom-up "reconstructive method" [76]. Stakeholder classifications that are defined by the stakeholders themselves during the stakeholder-mapping process are known as reconstructive methods. Analytical categorization, on the other hand, refers to the application of preset criteria, such as legitimacy and influence, cooperation and competition, cooperation and threat, and interest and influence [77]. Matrix analysis is frequently used for this [78].

The RACI matrix is one popular method for characterizing stakeholder roles and uses interest and influence to classify stakeholders through a "responsibility assignment matrix" [79]. The RACI model distributes authority, making power dynamics explicit by defining roles in a task, project or management activity [80]. It was selected for this study, as it was seen as more appropriate for broadly categorizing relative levels of importance in decision-making processes. It is also intuitive, can be explained easily and is readily understood by people with no prior familiarity with the RACI model. RACI refers to the following:

- Responsible: someone who bears the responsibility of seeing a task through to completion;
- Accountable: This means that everyone in the team is accountable for whatever work that is assigned to them. Additionally, this person is able to decide on matters pertaining to the assignment. This person is accountable for all of his decisions, which makes this role extremely important;
- Consulted: as they will be responsible for providing information on the project under work, those who are selected for this role possess expertise in their respective fields;
- Informed: those who receive regular updates on developments.

The RACI matrix has been used as a Six Sigma tool to identify those involved in the process and their roles in a productivity process corresponding to systems with uncertainty through the define, measure, analyse, improve and control (DMAIC) approach to the implementation of ISO 50001 [81]. This tool is very useful when implemented in continuous process improvements, both in industrial aspects and in business processes [82]. The use of the RACI matrix is recommended to define the tasks and responsibilities of those involved in a project, as well as to follow up on specific tasks and document clear and precise traceability. This prevents role confusion and ensures balance among all members of the project, and allows for assigning the corresponding progress in the process of completing each member's tasks [83]. Recently, a RACI matrix was developed to map the different actors involved in the process of using building information modelling for the evaluation of the certification of sustainable buildings in the Netherlands and the potential impact of these [84].

This research presents three stages to develop the implementation of the RACI matrix, which were (1) the determination of the organizations and their role according to interviews and electronic surveys, (2) the parameterization of the valuation of the respondents according to their judgments in the people surveyed and interviewed for the identification of the roles of each of those involved, and (3) the mapping of the roles of the organizations [85]. The matrix helps to ensure that all tasks and activities are assigned to appropriate organizations/individuals or roles, and that there is clarity about who is responsible for making decisions, performing tasks, providing input, and receiving updates. To complete the three stages for the implementation of the RACI, the following steps are needed: (1) Identify the Project: determine the specific project for which to create a RACI matrix; in this case, the deployment of urban wind technology. (2) Identify Key Activities and Tasks: Break down the project into its constituent and tasks. This involves defining the major steps, milestones, or deliverables involved. (3) Define Roles and Responsibilities: Identify the relevant roles of the institution involved in the process. This includes stakeholders or other parties with specific responsibilities. (4) Assign RACI Labels: assign the appropriate RACI label to each role or individual involved: Responsible (R), Accountable (A), Consulted (C), Informed (I). (5) Create the RACI Matrix: Construct a matrix with the identified information listed along one axis and the relevant roles along the other axis. Place the appropriate RACI label in each cell to indicate the role's responsibility for each task. (6) Review and Validate: Review the RACI matrix with the relevant stakeholders. Ensure that the roles and responsibilities are accurate, clear, and aligned with the project or process requirements. (7) Communicate and Implement: Share the finalized RACI matrix with the project team, stakeholders, and other relevant parties. Ensure that everyone understands their roles and responsibilities as defined in the matrix. Use the RACI matrix as a reference throughout the project or process to guide decision-making, task assignment, and communication. (8) Update and Maintain: As the project or process evolves, regularly review and update the RACI matrix as needed. Ensure that it remains up to date and reflects any changes in roles, responsibilities, or project requirements. A more detailed explanation of the overall research design is provided in the following steps.

- Rapid network assessment and experts interviews

This was to identify the key decision-makers and their motivations of the potential utilisation of urban wind energy. An egocentric network mapping technique was used. Egocentric network mapping is a method used in social network analysis to study the connections and relationships of a single individual, referred to as the "ego", within their immediate social network [86]. Information gathering on stakeholders roles was performed through primary interviews, network mapping techniques and the RACI Matrix. More precisely, the following activities were conducted: (i) a rapid network assessment (RNA) and (ii) an online survey. This step-by-step approach was designed to make it possible for pertinent stakeholders to encourage a larger group of actors to participate in the survey, starting with a known group that represented both government-and market-led approaches. After identifying the main stakeholders, all of whom are detailed in full below and currently hold titles such as junior, middle, or senior managers, they were asked to identify other pertinent figures in the energy sector as part of the RNA. Then, the participants of the online survey were notified. This method allowed for the identification and inclusion of any actor, whether a corporate entity or a government agency, which was thought to be a pertinent decision-maker. This procedure is explained in more detail below.

The RNA was created with the intention of producing a preliminary roster of key players for the energy sector decision-making processes in the Dominican Republic. From an initial list of stakeholders in the Ministry of Energy and Mines, the electricity generation and transmission companies, electricity distribution companies and the supply authority, power producers, universities, and research centres, NGO's and people involved in electricity supply decisions and policy making were identified to take part in this process. Based on the stakeholders who deal with electrification projects, the initial list of respondents for the online survey was completed. This procedure is called "snowball sampling". There were found to be a total of 132 professionals. After the RNA, an online survey was carried out. This survey was designed to use the RACI matrix to determine the typical role of important stakeholders in decision making. A total of 59 professionals completed the survey, representing a variety of organisational, professional and expertise backgrounds, as shown in Table 1, where 81% are engineers (electrical, mechanical, civil, etc.), 12% are lawyers who work directly in the energy and/or sustainability sector, and 7% correspond to the business and architecture fields. In general, the average experience is of 16 years.

- RACI Matrix Elaboration

To understand the relative importance of different stakeholders, the physical placement of the different stakeholders in the form of post-it notes on the RACI matrix was converted into X and Y coordinates, whereby the overall coordinates for each stakeholder were calculated by averaging the given coordinates for each stakeholder from all the interviewees [31]. Each set of coordinates in the RACI matrix was transformed to a single digit score, *S*. In the transformation, the following criteria was used:

- An accountable stakeholder (quadrant I) was awarded a score of 4, as shown in Equation (1), where X and Y are the coordinates of the stakeholder in the RACI matrix.

$$S = 4 - 0.5\sqrt{\left(1 - X\right)^2 + 9\left(1 - Y\right)^2} \quad (1)$$

- A responsible stakeholder (quadrant II) was awarded a score of 3, as shown in Equation (2).

$$S = 4 - 0.5\sqrt{\left(1 - X\right)^2 + 4\left(1 - Y\right)^2} \quad (2)$$

- A consulted stakeholder (quadrant III) was awarded a score of 2, as shown in Equation (3).

$$S = 1 - 0.5\sqrt{\left(1 - X\right)^2 + 4\left(1 - Y\right)^2} \quad (3)$$

- An informed stakeholder (quadrant IV) was awarded a score of 1, as shown in Equation (4).

$$S = 1 - 0.5\sqrt{\left(1 - X\right)^2 + 9\left(1 - Y\right)^2} \quad (4)$$

The score for each stakeholder was normalised by the fraction of interviews that identified the stakeholder as relevant to the decision making in the role given by the interviewees, as shown in Equation (5), where M is the number of interviews and S_{abs} is the average score.

$$S_{abs} = S\frac{M}{59} \quad (5)$$

- Mapping the RACI matrix

Finally, a mapping of the results is presented graphically to compare the assignment of the roles of each of the institutions according to the judgment of the interviewees. Likewise, the importance of each of these institutions in the role can be visually assigned. This mapping serves as a practical guidance representation that can be developed around RACI analysis.

Table 1. Network structure for stakeholder analysis.

Profesiononal Area	Years of Experience	Counter	%
Engineering	17	48	81%
Lawyer	12	7	12%
Bussiness	9	3	5%
Architecture	18	1	2%
	Avg. 16	Total 59	Total 100%

3. Results and Discussion

This research aims to present an evaluation of the urban wind potential with the complement of a decision-making tool for the identification of the roles of key actors through a RACI matrix. A methodology has been proposed that contains two phases; first, the determination of urban wind potential through free-access data from the NWP, with a spatial resolution of the mesoscale to quickly identify the region with the best potential, and, in the second phase, an analysis of the RACI matrix is introduced for the first time to the existing methodologies for the study of urban wind potential. The RACI matrix has been applied in various organisational applications of heterogeneous work groups to identify key actors and their roles for timely decision making.

Table 2 presents the urban potential of wind energy in the Dominican Republic. Through the data available from the NWP, provided by NASA's Prediction of Worldwide Energy Resource (POWER) meteorological datasets, 32 provinces of the country have been selected to determine the urban wind potential at 10 m height above the ground level. The most urbanized location in each province has been selected to analyse the urban potential. The datasets analysed correspond to a 2011 through 2021 timeframe. The provinces with the greatest potential are Montecristi, El Seibo, Puerto Plata, La Altagracia, La Romana and Pedernales, with average wind speeds (WS) of 6.63, 5.21, 5.13, 4.83, 4.83 and 4.50 m/s, respectively. In these provinces, there is an estimated potential between 1638 and 3045 kWh/y. The predominant wind direction (WD) is 86°, with respect to the north. Figure 3 shows graphically the wind speed map at 10 m height for the entire country. In the provinces with greater colour intensity, greater energy will also be produced annually, because the energy produced depends on the cubed value of the average wind speed and the SWTs' power curve.

Because it is important to discretize the provinces with the best wind energy power, it is also important to establish a relationship between the most favourable provinces and the most urban ones. Table 2 presents the area of each province and the population to determine a population density index (inhabit./km^2). Figure 4 shows the population density map that can be compared with the urban wind potential map in Figure 3. It has been observed that the provinces where there is great wind potential are the least urbanized; that is, they have greater rurality. For example, in the northwest part of both maps, Montecristi has the highest wind speed recorded at 6.63 m/s; however, the population density is 70 inhabitants/km^2, among the lowest. For the National District, a "star" was placed on the map so that the comparison can be seen on the colour scale of the other 31 provinces, because the density of the National District was 14,216 inhabitants/km^2, while the average of the other 31 provinces is 266 inhabitants/km^2. Figure 4 shows that the five most densely populated provinces are the National District, Santo Domingo, San Cristóbal, Santiago and La Romana, with densities ranging from 14,216 to 505 inhabitants/km^2, respectively. These are the provinces in which future research should be carried out to promote urban wind harnessing in densely populated provinces.

Because NWPs are a wide spatial resolution technique, this investigation not the aspects of orography and roughness of the terrain have been disregarded, so those must be validated through on-site measurement for small-scale evaluation and must be carried out in order to study the micro-scale resolution a few meters around the SWTs [61]. When using open access geographic reference systems tools provided by NASA for wind energy analysis, it is important to consider their reliability and limitations. Reliability: NASA's tools often utilize data from reliable sources, including satellite observations and numerical weather-prediction models. These sources undergo extensive validation and quality control processes to ensure accuracy and reliability. Expertise: NASA employs experts in remote sensing, atmospheric sciences, and geospatial analysis who develop and maintain these tools. Their scientific expertise ensures the tools are built on sound methodologies and cutting-edge research. NASA conducts validation studies and intercomparison exercises to assess the accuracy and reliability of the tools. These studies help to validate the performance of the tools against ground-based measurements. Limitations: The spatial and temporal resolution of NASA's geospatial data may not always align with the specific requirements of wind energy analysis. The resolution may be coarse, limiting the ability to capture localized wind patterns accurately. Some NASA tools provide near-surface wind data, which may not be sufficient for wind energy analysis that requires information on wind speed and direction across various heights. Additional measurements or modelling may be needed to estimate the wind profile variation with the height. NASA's tools may not consider site-specific factors that influence wind energy potential, such as local topography, land use, or obstacles. These factors can significantly impact wind resource assessment and turbine performance. While NASA's data sources undergo validation, there may still be inherent uncertainties associated with the measurements and models. NASA's tools often provide raw or pre-processed data that may require additional processing, calibration, or integration with other datasets for wind energy analysis. While NASA's tools can provide wind resource data, estimating the energy yield of a wind energy project requires additional considerations, such as turbine characteristics, wake effects, and electrical grid constraints.

Table 2. Urban wind energy and population data by provinces.

Privinces	WS at 10 m (m/s)	WD at 10 m (°)	AEP (kWh/yr)	Area (km^2)	Population (Inhabit.)	Population Density (Inhabit./km^2)
Azua	3.97	86	1464	2532	256,981	101
Bahoruco	3.15	117	722	1282	118,987	92
Barahona	4.12	92	1638	1739	226,898	130
Dajabón	3.93	60	1416	1021	67,887	66
Distrito Nacional	3.41	80	919	104	1,484,789	14,216
Duarte	3.46	87	964	1605	384,789	239
Elías Piña	2.57	80	385	1426	70,589	49
El Seibo	5.21	82	3162	1787	115,889	64
Espaillat	2.72	88	461	839	390,478	465
Hato Mayor	3.29	82	828	1329	89,578	67
Hermanas Mirabal	2.72	88	461	440	103,974	234
Independencia	3.15	117	722	2006	54,785	27
La Altagracia	4.83	81	2587	3010	335,677	111
La Romana	4.83	81	2587	654	330,587	505
La Vega	3.02	90	632	2287	420,478	183
María Trinidad Sánchez	3.46	87	964	1272	140,784	110
Monseñor Nouel	3.02	90	632	992	201,474	203
Montecristi	6.63	73	5197	1924	135,710	70
Monte Plata	2.19	84	236	2632	200,454	76
Pedernales	4.50	95	2121	2075	38,941	19
Peravia	3.97	86	1464	792	298,747	377
Puerto Plata	5.13	90	3045	1853	490,733	264
Samaná	3.29	82	828	854	168,265	126
Sánchez Ramírez	2.19	84	236	1196	248,807	131
San Cristóbal	3.41	80	919	1266	859,741	679
San José de Ocoa	3.97	86	1464	855	82,458	96
San Juan	3.20	99	761	3569	300,476	84
San Pedro de Macorís	4.07	82	1572	1255	418,850	333
Santiago	2.72	88	461	2837	1,833,451	646
Santiago Rodríguez	3.83	78	1313	1111	164,941	148
Santo Domingo	3.41	80	919	1302	2,995,211	2310
Valverde	3.83	78	1313	823	207,447	251

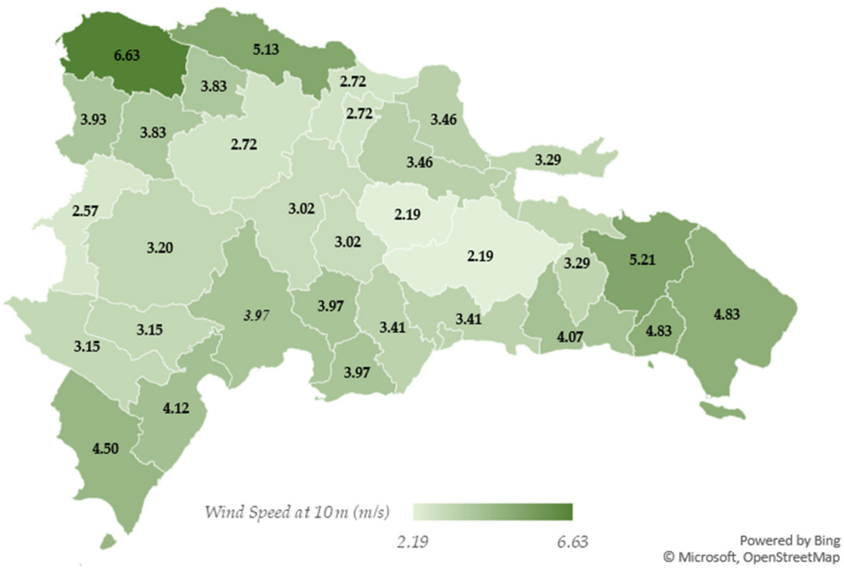

Figure 3. Uban wind speed at 10 m height by provinces in the Dominican Republic.

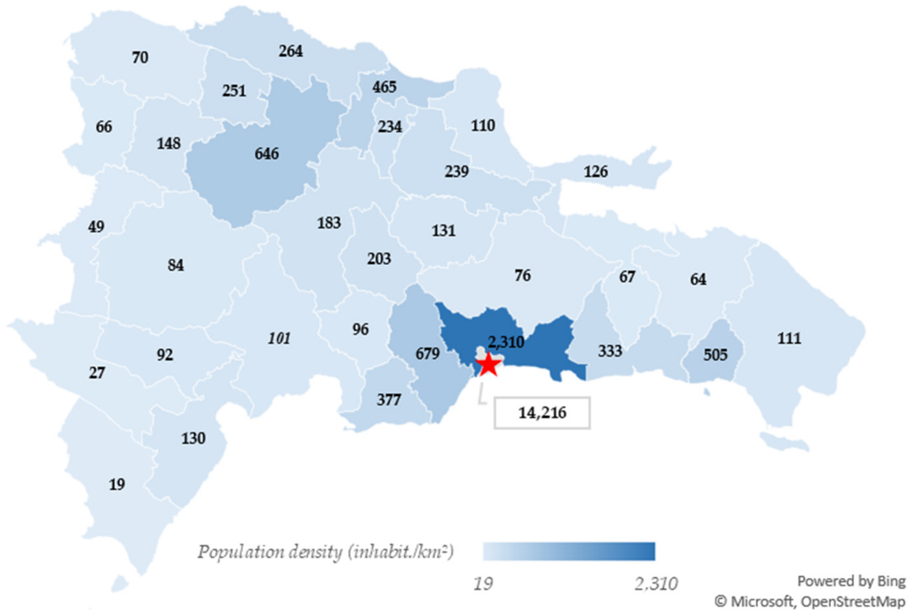

Figure 4. Population density by provinces in the Dominican Republic.

It is recommended to validate the results with on-site measurement campaigns, because estimation errors of the order of 33% have been reported, where NWP usually overestimates wind speed [87]. However, as height above ground level can be gained, SWTs can produce more energy, because they will be exposed to a greater frequency of high wind speeds, and this makes these types of distributed energy projects more economic. For buildings between 100 and 150 m height, the levelized cost of energy becomes more competitive [41]. No provinces with exceptional potential were identified; only Montecristi is considered very good (5.4–6.7 m/s). El Seibo, La Altagracia, La Romana, Pedernales and Puerto Plata have a moderate potential (4.5–5.4 m/s), and the rest have a poor potential (<4.5 m/s) [88]. For more information on the monthly and seasonal wind potential in the Dominican Republic, please refer to the papers presented in refs. [24,27,29].

Twenty-eight institutions were identified, both public and private, for-profit, and non-profit, and with direct or indirect relationship to the energy sector. An electronic survey form was sent to 132 professionals from various disciplines. Table 3 shows a summary of 28 institutions assessed by 59 professionals. The online surveys were administered through Google Forms, and the results were analysed using an Excel spreadsheet.

The stakeholders were identified first, based on individuals' positions in institutions related to electrification projects, and once they completed a primary list of respondents, those respondents proposed some other participants who should be involved in the online survey; this was performed with several groups following a procedure called "snowball sampling". There were found to be a total of 59 stakeholders.

Participants in the survey selected the role of each institution, such as "R", "A", "C", and "I". Figure 5 shows the quantity of roles assigned by participants. For example, the electricity distribution companies (EDE) obtained a higher share as "R", 46%, since 27 professionals consider the to be EDE classed as "R".

After the respondent assigns a role in the RACI matrix to an institution, then a value of importance is assigned to each, ranging from 1 (20%) to 5 (100%), called "relevance". It is calculated as the product between the value of the RACI letters obtained by Equations (1)–(4) and the degree of relevance of 20–100%. Table 3 presents the average coordinate for each institution, according to the judgment of all respondents in the X and Y axis, and Z represents the relevance. Relevance indicates how strongly respondents felt about the role they assigned to each institution. For example, a role of "R" and a score of 5/5 means that the respondent is totally confident in their decision of that role.

Table 3. Institutions' role assignment and relevance.

No.	Institution List	Accronys	X-Axes	Y-Axes	Z-Axes (Relevance)
1	Municipal councils	AYTO	0.03	0.09	0.49
2	Ministry of Energy and Mines	MEM	0.36	0.64	0.75
3	Electricity Distribution Companies	EDE	−0.34	0.40	0.61
4	National Energy Commission	CNE	0.16	0.16	0.16
5	Superintendence of Electricity	SIE	0.26	0.40	0.70
6	Coordinating Entity	OC	−0.13	−0.36	0.39
7	Dominican Electric Transmission Company	ETED	0.09	0.09	0.09
8	Universities	UNIV	−0.33	−0.40	0.37
9	National Industrial Property Office (ONAPI)	ONAPI	0.25	−0.36	0.21
10	Ministry of Higher Education, Science and Technology	MESCyT	0.19	−0.36	0.27
11	International Cooperation Organizations (USAID, UNDP, GIZ)	OCI	−0.31	−0.56	0.35
12	NGOs	ONG	−0.19	−0.44	0.31
13	Ministry of Industry and commerce	MIC	0.10	−0.14	0.35
14	Ministry of Economy, Planning and Development	MEPyD	0.09	−0.16	0.36
15	Ministry of Labor	MT	0.38	−0.29	0.18
16	Ministry of Environment and Natural Resources	MIMARENA	0.01	0.04	0.55
17	Superintendence of Banks	SB	0.24	−0.27	0.28
18	Local banks	BL	0.10	−0.24	0.33
19	International Cooperation Banks	BI	−0.09	−0.25	0.38
20	National Meteorological Office	ONAMET	−0.20	−0.36	0.37
21	Dominican Association of the Electrical Industry	ADIE	−0.19	−0.43	0.34
22	Association for the Promotion of Renewable Energies	ASOFER	−0.27	−0.22	0.46
23	National Association of Young Entrepreneurs	ANJE	0.11	−0.32	0.27
24	Association of Energy Efficiency and Renewable Energy Companies	AEEER	−0.19	−0.15	0.41
25	National Congress	CN	0.18	0.32	0.59
26	Supreme Court of Justice	SCJ	0.30	−0.05	0.33
27	Ministry of Education	MINERD	0.28	−0.31	0.24
28	Construction entrepreneurs	EC	−0.06	−0.27	0.35

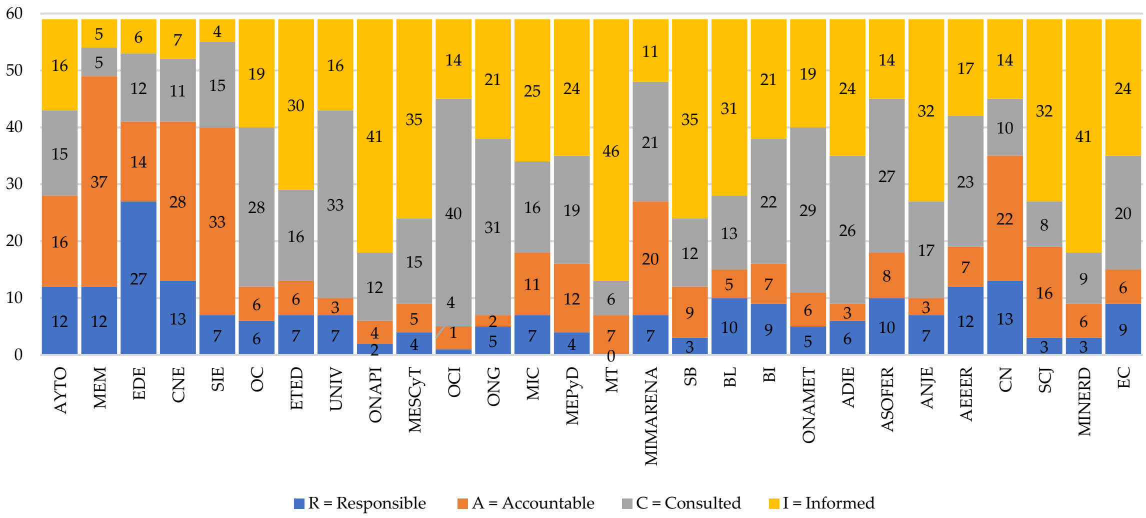

Figure 5. RACI categories and relevance by institution, according to expert judgement.

Figure 6 presents the RACI matrix roles of the 28 institutions evaluated by 59 experts. According to the experts' criteria, in quadrant A, there are companies in the energy sector that are key players in the planning, regulating, coordinating and supervising of the electricity market, such as MEM, SIE and CNE. In the R quadrant, there are only electricity distribution companies, and a shortage of responsible companies according to the experts' judgment. In the C quadrant, there are academic institutions, and many associations of renewable energy and energy efficiency businesses, as well as banks. And, finally, in quadrant I, there are the ministries related to labour, education, commerce, and local banking. On the other hand, the MIMARENA (Ministry of Environment and Natural Resources) and the Municipal Councils have a role of A, towards the centre of the cartesian plane, indicating that the evaluation from the experts' point of view has been assessed as being more biased.

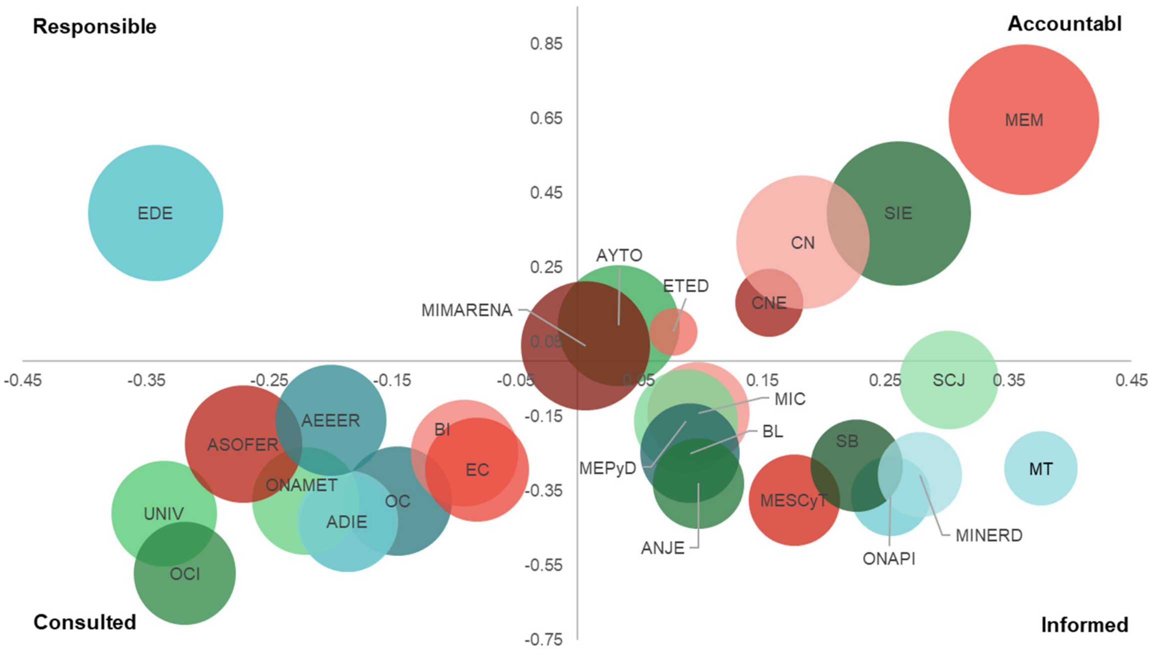

Figure 6. RACI stakeholder mapping for decision making in the urban wind energy in Dominican Republic.

Another 10 institutions emerged as recommendations from 16 surveyed experts. The most prominent are the Ministry of Public Works and Communications (31%), the General Directorate of Customs (13%), the Dominican Institute of Civil Aviation (13%) and other ministries such as the treasury, internal taxes, and the climate change council (18%). The rest of the institutions are part of a national security cluster (25%).

The findings from urban wind utilisation in the Dominican Republic can provide insights that may generalize to other urban settings. The findings regarding wind resources can offer generalizable knowledge about the potential for urban wind energy in other similar locations. Understanding the wind patterns, prevailing directions, and wind speeds in the urban areas can provide a basis for comparison with other urban settings. The characteristics of urban wind flow, including the effects of buildings, terrain, and other obstacles, can be similar across different urban environments. The findings can contribute to the understanding of how these factors impact wind energy potential in urban areas more broadly. Assessing the performance of wind turbines in the Dominican Republic's urban settings can provide insights into turbine technology and design considerations that may apply to other urban locations. Understanding the challenges and opportunities for SWT operation, efficiency, and output can inform similar projects elsewhere. The findings related to the policy and regulatory aspects of urban wind utilisation can offer lessons for other jurisdictions. This includes understanding the incentives, barriers, and strategies for promoting urban wind energy integration and navigating regulatory frameworks specific to urban contexts. Finally, the socio-economic factors associated with urban wind utilisation in the Dominican Republic, such as community engagement, public acceptance, and economic feasibility, can provide valuable insights for similar projects in other urban areas. Understanding the social and economic dynamics surrounding urban wind projects can help guide decision-making and stakeholder engagement efforts.

4. Conclusions

Urban wind energy has emerged as a promising source of distributed energy generation in cities to achieve sustainable development goals. The advancements in technology have made urban wind energy a viable option for decarbonising cities and transitioning to cleaner energy sources. The study focused on assessing the wind energy potential in the Dominican Republic using numerical weather prediction (NWP) data tools. The results showed that most provinces have poor wind potential, while others, particularly in the northwest and east, have significant potential, with average wind speeds ranging from 4.83 to 6.63 m/s. This research also identified and analysed the stakeholders involved in the decision-making process related to energy projects. Twenty-eight institutions were identified through interviews, and their roles were evaluated using the Responsible, Accountable, Consulted, and Informed (RACI) matrix. The identified stakeholders included government-owned electricity companies, energy associations, universities, and educational and justice institutions. The findings revealed the importance of considering various stakeholders' perspectives and involvements in decision-making processes for the effective implementation of urban wind energy projects. This inclusive approach ensures that decisions align with the interests and priorities of different stakeholders and considers the social, environmental, and economic aspects of energy projects.

This study emphasized the need for decision-making tools that can identify hidden factors and overcome challenges in implementing distributed technologies in urban environments. These tools play a crucial role in supporting the energy transition and facilitating the adoption of renewable energy technologies, grid flexibility, and decentralised energy solutions. This research highlighted the potential of building-integrated wind turbines as a sustainable solution for reducing the carbon footprint of buildings in urban areas. By harnessing urban wind energy, cities can contribute to a clean and environmentally sustainable energy generation.

Overall, the study provides valuable insights into the wind energy potential in urban areas and the stakeholders involved in energy decision-making. It underscores the importance of considering renewable energy sources like urban wind energy in achieving global sustainability goals and transitioning to low-carbon energy systems.

The findings on urban wind energy policy and planning suggest several significant implications. Policymakers can develop and strengthen policies to promote wind energy adoption in cities, utilizing incentives and regulations to encourage installations. Strategic planning based on wind energy potential can optimize resource allocation and investment decisions. Aligning with sustainable development goals, integrating wind energy can reduce emissions and improve air quality.

Stakeholder engagement is important, as identifying key actors and their roles fosters collaboration and informed decision making. Technological considerations, such as site-specific conditions, should be factored in for optimized turbine positioning. Decreasing costs make urban wind energy economically viable, attracting private sector participation and funding. By considering these implications, policymakers can drive sustainable urban wind energy deployment and transition to clean energy sources.

This study on urban wind energy policy and planning has several potential limitations. Data accuracy and availability could affect the reliability of wind energy potential estimates and stakeholder identifications. The findings may not be generalizable to other regions due to variations in local factors. The use of snowball sampling for stakeholder identification may introduce bias and limit representation. Technical aspects such as wind turbine design and grid integration may not have been thoroughly explored. Socio-economic factors and community acceptance were not explicitly addressed. The study may not have extensively analysed the existing policy and regulatory frameworks. These limitations should be considered when interpreting the findings, and further research should address these gaps for a more comprehensive understanding of urban wind energy policy and planning.

Future research in urban wind energy policy and planning should focus on conducting detailed wind-resource assessments, collecting long-term data, performing economic analyses, engaging stakeholders, analysing policy frameworks, exploring technological advancements, and conducting comparative studies between urban areas. By addressing these research gaps, future studies can enhance our understanding of urban wind energy, inform decision-making processes, and contribute to the development of effective and sustainable strategies for implementing wind energy in urban environments.

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