Application of the MACTOR Method for the Analysis of the Impact of Key Actors in the Development of Materials for Energy Applications

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Abstract: This article analyzes the power interactions and strategic relationships of the most important actors in the development of materials for energy applications using the MACTOR methodology, with the aim of assessing their potential in promoting sustainability, technological innovation, and the implementation of advanced energy policies. Nine actors are presented and analyzed, including governments and regulatory entities, energy companies, private finance, technology suppliers, research centers, and consumers.
The results of this research show that governments and research institutions have significant power over the rest of the actors, specifically in the promotion of standards and in the production of knowledge and technological innovation. Both technology providers and energy companies are key linking actors, fundamental for the implementation and adoption of new solutions. On the other hand, there is a weak convergence of NGO and consumers, which is a good opportunity to improve the relationship of these actors within the system and the social acceptance of advanced energy technologies.
The study concludes that strategic coordination and alignment of interests between these actors are essential to ensure the development of sustainable materials, compliance with international regulations, and the promotion of equity in access to energy technologies. In addition, it highlights the need to prioritize objectives related to social acceptance and professional training to maximize the positive impact on the energy sector.

Keywords: sustainable development, key actors, technological innovation, energy policies, inter-institutional collaboration.

1. Introduction

Progress in the development of energy materials such as energy storage, conversion, and application is crucial on the path toward a future with a more sustainable and efficient energy system (Aftab et al., 2021). The demand for the use of clean energy and the global agreements signed to reduce greenhouse gas emissions have pushed research groups and organizations to carry out studies focused on the development of new energy materials (Chu & Majumdar, 2012). The connection between the different groups of people (industry, academia, and public administrations) that play a fundamental role in the research and development (R&D) processes in the practice of executing emerging technology is decisive (Grimpe, 2007).

The MACTOR method (Matrix of Actors, Objectives, and Relationships) has been used in various contexts for analyzing and modeling the influence of interdependence exerted by actors in complex systems. To cite an example, Godet (1991) made use of the technique for its application in strategy planning while Macioszek et al. (2023) identified and classified the actors that influence the sustainable development of energy-efficient electric scooter sharing systems in Polish cities. Within the line of energy materials, the most recent research has shown the need to develop the coordination of interdisciplinary efforts to face technical and social challenges (Colombo & Mattarolo, 2017).

Despite all the advances in the development of energy materials, the literature points out that challenges persist due to the lack of alignment between the objectives of the key actors (industry, academia, and government). This disarticulation of objectives affects the coordination and effective implementation of energy solutions, since success in energy materials innovation requires interdisciplinary and strategic collaboration (Sperling & Berke, 2017), as suggested in studies carried out by Cummings and Kiesler (2005) and Larcher & Tarascon (2015), which highlight the need to articulate priorities between the different actors involved. Likewise, the lack of a resource analysis between the actors prioritized by the actors limits the design of a collaboration strategy (Alkaraan et al., 2023).

This research is important insofar as it allows for a better understanding of the dynamics of the actors involved in the development of materials for energy applications. Identifying reciprocal interactions and main strategic priorities is precisely what the MACTOR methodology (Arcade et al, 2014) provides, which allows for designing more effective R&D policies and strategies. This procedure is particularly relevant in the current international context where sustainable energy solutions and cooperative alternatives are required.

The main objective of this research work is to identify the impact or influence of key actors in the development of materials for energy applications with MACTOR. This methodology allows for a systematic and visual analysis of the relationships within the context of the actors, as well as the opportunities, or threats, present in the development of energy materials. It also provides recommendations for improving the coordination and effectiveness of cooperative efforts and contributes to the literature on prospective analysis and innovation management in particular (Enserink et al., 2022).

2. Methodology

This study is exploratory-descriptive in nature since the objective is to analyze, through the MACTOR methodology, the influence of key actors in the development of materials for energy applications (Casula et al., 2021). This approach is one of the most appropriate to analyze the relationships, influences, and strategies developed by actors in a network framework (Godet, 1994). The research strategy is transversal, and since the collection of information is carried out at a given time, it allows obtaining a single visual representation of the interactions and priorities of the actors involved (Dell’Anna & Dell’Ovo, 2022).

Twelve experts in materials for energy applications were included through purposive sampling. The choice of 12 participants is based on the literature referring to MACTOR, which considers that a small but representative number of experts is ideal for obtaining rich and relevant information for the prospective analysis study (Godet, 1994). Each of the selected experts met the following criteria: minimum experience of 5 years in the sector, representation of different types of actors (industry, academia, and government sector), and active participation in projects related to energy and materials.

To carry out this research, it was first decided to start with a prior documentary review and preliminary consultations with experts to identify the relevant actors. Following this, the MACTOR software was used for data collection and processing. The experts were called to participate in structured workshops where they were asked to identify the key objectives, influences, and dependencies between the actors. The results were presented to the experts for validation of their interpretation and to make any necessary adjustments (Godet, 1991). This procedure meets the requirement of a systematic approach to capture the different perspectives of the key actors and analyze the complex relationships between them.

The data were processed and analyzed using MACTOR software, which allows the identification of the strategic positions of the actors, their key objectives, and the reciprocal relationship of influence (Arcade et al., 2014). Direct and indirect influence matrices and power maps were generated to capture the nature of the system and the possibilities of the existence of the scenarios.

Regarding the study's limitations, although the 12 selected experts are representative, their number may not cover all existing perspectives. However, this strategy is common in exploratory studies where the depth of analysis prevails over the sample size (Swedberg, 2020). In addition, the experts' opinions are affected by their experiences and context, which leads to the introduction of biases. This is reduced by data triangulation and validation of results.

3. Results

For this study, the most relevant actors in the sector were included through purposive sampling and analysis of secondary sources, as described in the methodology. These actors play different strategic roles that directly affect the development, adoption, and sustainability of advanced materials for energy applications. Table 1 presents the actors, assigning them a code and describing their role in the system.

Table 1. List of identified actors that influence the development of materials for energy applications

Code	Name	Role
A1	Governments and regulators	They define energy policies, encourage research and ensure compliance with environmental and technological standards.
A2	Energy industries	They demand new materials to improve operational efficiency and the energy transition towards renewable sources.
A3	Private investors and capital funds	They provide financial resources for innovation projects in advanced materials.
A4	Raw material and component suppliers	They supply the necessary inputs for the production of advanced materials.
A5	Technology and innovation suppliers	They develop new technological solutions in materials for implementation in energy applications.
A6	Non-governmental organizations (NGOs)	They promote sustainability, monitor environmental and social impact, and generate pressure on public and private actors.
A7	Research institutions and universities	They lead scientific development, innovation and technology transfer in energy materials.
A8	International organizations	They promote global cooperation on energy sustainability and finance large-scale projects.
A9	Consumers and communities	They represent the final demand for energy products and materials, influencing their acceptance and adoption.

Source: Authors

The objectives were also identified through a literature review and consultations with experts in the sector. These objectives reflect the common priorities of the actors in the context of the development and adoption of advanced materials. The list of objectives together with their corresponding code is presented in Table 2.

Table 2. List of strategic objectives in the development of materials for energy applications

Code	Objectives
O1	To promote the development of sustainable materials, with low environmental impact and high performance.
O2	To reduce production costs and ensure the affordability of energy materials.
O3	To comply with international sustainability and energy efficiency regulations
O4	To promote research and technology transfer in innovative materials.
O5	To promote public policies that facilitate the adoption of advanced energy technologies.
O6	To increase social and community acceptance of new materials and technologies.
O7	To guarantee global and equitable access to materials and technologies for energy applications.
O8	To improve energy efficiency and durability of materials in practical applications.
O9	To train professionals and industries in the implementation of advanced energy technologies.

Source: Authors

The above information was entered into the MACTOR software in order to complete the influence matrices and the matrix of valued positions of the objectives and the actors, with which the following results were obtained.

Influence and dependency of actors in the development of materials for energy applications

In the plane of influences and dependencies (Figure 1), actors are classified according to their level of influence on the system and their dependency on others.

Dominant actors (high influence and low dependency): A1 (Governments and regulators), A7 (Research institutions and universities), and A8 (International organizations); Linking actors (high influence and high dependency): A2 (Energy industries), A5 (Technology and innovation suppliers), A3 (Private investors), and A4 (Raw material and component suppliers); Autonomous actors (low influence and low dependency): A6 (NGOs); Dominated actors (low influence and high dependency): A9 (Consumers and communities).

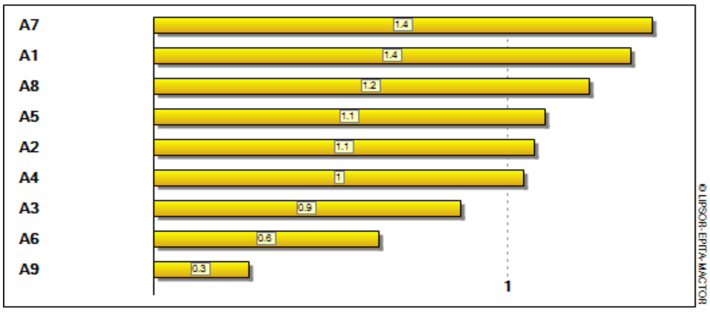
Figure 1. Plane of influence and dependency positions of actors

Source: Authors

Power relationships between actors

The analysis of the power relationships (Figure 2) shows that the strongest actors are A7 (Research institutions) and A1 (Governments and regulators), followed by A8 (International organizations); the actors with intermediate strength are A5 (Technology providers), A2 (Energy industries), and A4 (Raw materials and components providers); the actor with the least strength is A9 (Consumers and communities), although its role is relevant in terms of sustainability and social acceptance.

Figure 2. Histogram of the power relationships of the actors

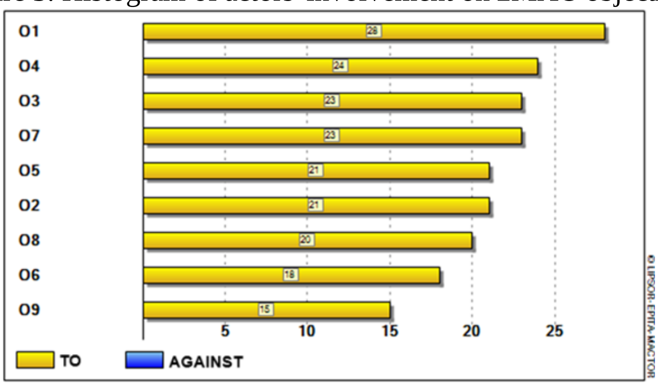


Source: Authors

Positioning of actors in relation to objectives

The commitment and capacity of the actors concerning the strategic objectives are presented in two histograms: in the commitment histogram (Figure 3), the objectives with the highest commitment were O1, O4, O3, and O7; objectives with medium commitment were O5, O2, and O8, and the objectives with the lowest commitment were O6 and O9.

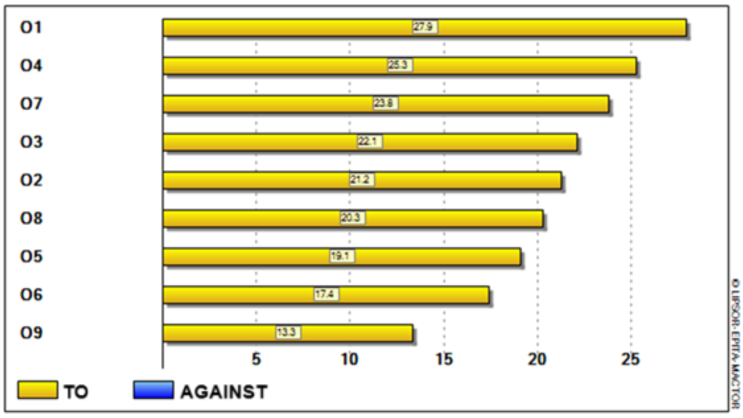
Figure 3. Histogram of actors' involvement on 2MAO objectives



Source: Authors

On the other hand, the histogram in Figure 4, which reflects the actors' ability to act on the objectives, shows a high capacity to achieve objectives O1 and O4; a medium capacity for O7, O3, O2, O8, and O5; while the objectives with the lowest capacity were O6 and O9.

Figure 4. Histogram of actors' involvement on 3MAO objectives

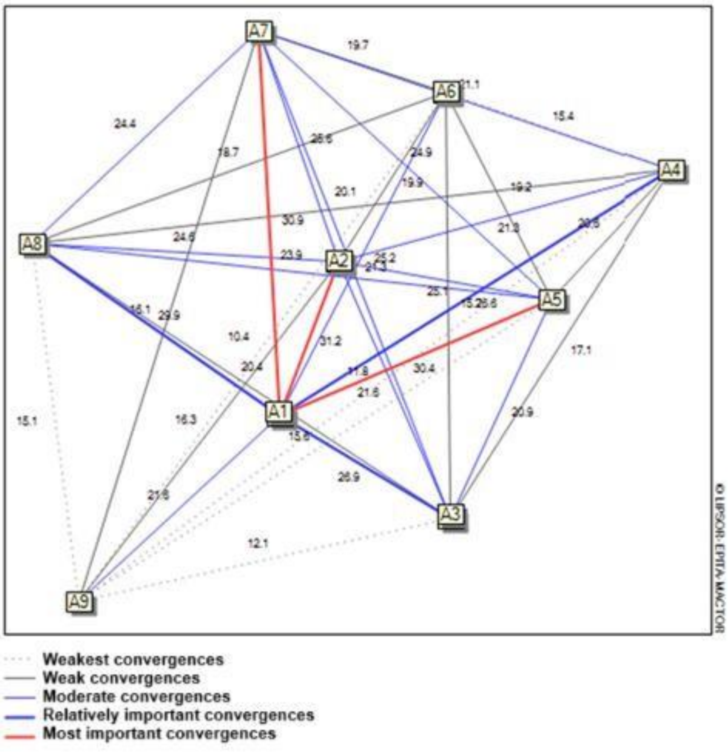


Source: Authors

Convergences and alliances between actors

The analysis of convergences between actors reveals the following convergences (Figure 5): prominent alliances between A1 and A7, A2, and A5, which share strategic interests in innovation and sustainability. Weak convergences: A6 and A9 have less alignment with dominant actors, but are key to social acceptance and sustainability.

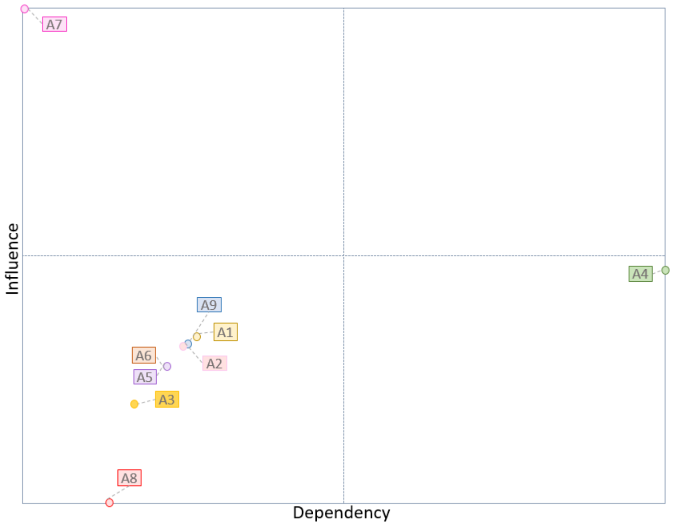
Figure 5. Graph of convergences between actors



Source: Authors

On the other hand, no divergences were found, which is why the possible alliances between them are analyzed using the plane of net distances shown in Figure 6. In this plane, two groups are distinguished: on the one hand, the closest actors that represent the suppliers of raw materials and components A4 and research institutions and universities A7; and, on the other hand, the actors that manage and consume these services, such as A1, A2, A3, A5, A6, A8, and A9.

Figure 6. Plane of net distances between actors



Source: Authors

Interpretation and discussion of results

The findings of this study provide a representation of the power dynamics and influence relationships of key actors in the development of materials for energy applications. This analysis identifies different roles and degrees of influence exerted by actors in the system, allowing insight into their specific contributions and challenges in advancing strategic objectives.

The three results show that the central actors are Governments and regulators (A1), Research Institutions and Universities (A7), and International Organizations (A8), which have a high influence and a low dependency or need; in this way, their preferential place allows them to be fundamental for the change of direction of the system in relation to sustainability and innovation, with the literature agreeing in pointing out that they are irreplaceable actors to establish regulatory frameworks, promote research, and guarantee the adoption of sustainable practices (Adams et al., 2016). Research Institutions (A7), in particular, play a fundamental role in providing knowledge and in the development of technological transfer (Correa & Zuniga, 2013), and International Organizations (A8) promote global standards and financing to promote sustainable initiatives (Pandey et al., 2022).

Linking actors, such as Energy Industries (A2), Technology and Innovation Suppliers (A5), Private Investors (A3), and Raw Materials and Components Suppliers (A4) are actors with high influence and high dependency, which emphasizes their role in the implementation of technological solutions and the development of basic infrastructure. Their role as actors is fundamental when it comes to promoting sustainable energy materials and reducing production costs concerning O1, O2, and O4 (Lund, 2009).

Non-governmental organizations (A6) have low influence and low dependency, that is, they are autonomous actors, and although their direct influence is limited, these organizations are crucial in promoting social acceptance and ensuring transparency in the implementation of new energy technologies. The literature points out the role these organizations play in favor of sustainable practices and community awareness as stated in (Hildingsson & Johansson, 2016).

Consumers and communities (A9) show a high dependency and low influence, constituting themselves as dominated actors. However, their role is significant at the level of sustainability and social acceptance within the framework of objective O6. The literature shows the relevance of including communities in decision-making processes in favor of sustainability and the success of advanced technologies as demonstrated in the studies carried out by Fraser et al. (2006).

On the other hand, the analysis of the power relations indicates that the strongest actors are the Research Institutions (A7) and the Governments and regulators (A1), although they are followed by the International Organizations (A8), results that reinforce the assertion of the tension between research, regulation and international cooperation in energy materials. The actors of intermediate strength are the Technology Suppliers (A5), the Energy Industries (A2), and the Raw Materials Suppliers (A4), and they are above the Consumers and communities (A9) that have less relative strength, but as revealed previously, these actors are important in terms of social acceptance and sustainability (Irvin & Stansbury, 2004).

Regarding the objectives, the results show high involvement with the development of sustainable materials (O1) and research and technology transfer (O4), which are consistent with studies carried out by Hildingsson and Johansson (2016), which show how these aspects constitute the fundamental pillars in the energy transition. On the other hand, the objectives with low involvement would be social acceptance (O6) and professional training (O9), aligning with patterns found by Franco and Tracey (2019) where the lack of an inclusive strategy toward communities that strengthen local capacities is observed.

The analysis of convergences has shown the presence of significant alliances between Governments and regulators (A1) and Research Institutions (A7), as well as between Energy Industries (A2) and Technology Providers (A5) that share strategic interests in innovation and sustainability. The weakest convergence is represented by NGOs (A6) and Consumers and Communities (A9). The results obtained are also aligned with studies that underline the importance of strategic alliances in taking advantage of system efficiency (Pinilla-De La Cruz et al., 2022).

Similarly, Sutherland et al. (2016) found that A6 is normally dedicated to achieving macro objectives, for example focusing on public policy, sustainability of the global situation, and advocacy, while A9 shows more immediate and tangible interests, for example in direct access to materials or technologies. This can lead to a significant distance at the level of shared strategic objectives.

The plane of net distances shows two main groups: nearby actors, such as Raw Material Suppliers (A4) and Research Institutions (A7), which represent solution providers; and actors that manage and consume these services, such as Governments (A1), Energy Industries (A2), and Consumers (A9). This structure suggests that collaboration between suppliers and end-users is essential to ensure the sustainability and efficiency of the system (Colombo & Mattarolo, 2017).

The results of this study present several relevant strategic implications for the design and implementation of policies and projects in the materials sector for energy applications:

Strengthening the role of dominant actors: Given the high level of influence of governments (A1) and research institutions (A7), it is crucial to design policies that integrate these actors in the development and implementation of innovative technologies. Government institutions should prioritize the creation of tax incentives and subsidies that encourage research and technological development.

Fostering public-private alliances: The agreements seen between actors such as A1, A2, and A7 demonstrate the importance of establishing strategic alliances that combine regulatory, industrial, and academic capabilities. Collaboration platforms can help to transfer technology and accelerate the capacity to act to introduce sustainable solutions.

Increasing social and community inclusion: The low influence of consumers and communities (A9) and NGOs (A6) highlights the need to introduce strategies regarding civic participation and education to achieve social acceptance and promote common ownership of new energy technologies.

Prioritizing professional training: Low engagement and low capacity observed in training objectives (O9) are obstacles to the effective adoption of cutting-edge technologies. Sector actors must invest in technical training programs that prepare professionals to work with new materials and technologies.

Promoting sustainability and cost reduction: Sustainability (O1) and cost reduction (O2) are vital aspects for universal access to materials and energy technologies. This implies establishing strategies that impact the value chain, that is, taking it into account from the acquisition of raw materials to their production and distribution.

Addressing gaps in social acceptance and durability of materials: Despite high capacity in sustainability, low convergence on objectives for social acceptance (O6) and improved durability (O8) is an indicator that considerable efforts should be made to strengthen these two areas to ensure the long-term success of advanced energy technologies.

Taken together, these strategic implications demonstrate that there must be an integrated approach that introduces technological innovation with social inclusion and cross-sector collaboration to address the global challenges of the energy sector.

4. Conclusions

This study, by applying the MACTOR method, provides a detailed insight into the power dynamics and strategic influence among key actors in the development of materials for energy applications. The results show how each actor group (governments and regulators, energy industries, private investors, research institutions, and consumers) plays a key role in promoting sustainability, technological innovation, and the implementation of energy policies.

The analysis reveals both cooperative and divergent relationships between actors. For example, research institutions and technology providers tend to collaborate on innovation and technology transfer, while tensions arise between governments, energy industries, and private investors regarding financing and sustainability policies. These dynamics reflect a complex power structure where the specific interests of each actor (such as technological development of suppliers, environmental sustainability of governments, or social acceptance of consumers) require alignment to achieve the overall objectives of the energy system.

The identified power dynamics suggest that while there are significant challenges, such as the need for balanced regulation and the integration of consumers and NGOs into the system, significant opportunities also exist. In particular, alliances between governments, research institutions, and technology providers have the potential to accelerate the development of sustainable materials and ensure their large-scale implementation. However, low commitment to objectives such as social acceptance (O6) and professional training (O9) highlights critical areas that require attention, aligning with the literature that highlights challenges in the adoption of innovative technologies and in preparing actors to face the demands of the energy sector.

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