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Bayesian networks for assessing the sustainability of the marine renewable energy sector in the blue economy of Spanish ports

Javier Vaca-Cabrero *, Nicoletta González-Cancelas, Alberto Camarero-Orive

Department of Transport, Territorial and Urban Planning Engineering, ETSI Caminos, Canales y Puertos, Universidad Politécnica de Madrid, calle Profesor Aranguren, 3, 28040 Madrid, Spain

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A B S T R A C T

This research focuses on identifying key indicators for the sustainable development of the Marine Renewable Energy sector in the Blue Economy of Spanish ports, utilizing Bayesian networks to integrate economic, social, and environmental perspectives. The study also aims to develop a decision-support tool for strategic planning in ports. The methodology involves creating and analyzing a Bayesian model using data from 28 Spanish port authorities. The study includes selecting indicators, data preprocessing, and model construction to identify interrelations among sustainability variables. Key findings indicate that economic investment in port infrastructure, environmental characterization, and occupational safety are crucial factors for the sector's development. Bayesian networks enabled the representation of relationships among these indicators, highlighting the importance of a balanced approach between economic, social, and environmental sustainability. The study concludes that the sustainability of the Marine Renewable Energy sector depends on an effective integration of economic investments, environmental management, and occupational safety measures, supported by tools like Bayesian networks to optimize decision-making in the port sector.

1. Introduction

The development of the Blue Economy, understood as an economic model that promotes the sustainable use of ocean resources to drive economic growth, improve livelihoods, and preserve marine ecosystems, is essential for European ports, particularly in the marine renewable energy sector. This economy promotes the sustainable management of ocean resources, fostering innovation and economic growth o [27]. Ports play a fundamental role as hubs for the development of marine renewable energies, fostering the energy transition and reducing pollution. This strategy strengthens both port competitiveness and the sustainable development of European coastal regions, significantly contributing to achieving sustainability objectives and ensuring the future of the maritime sector [41].

The Marine Renewable Energy sector is one of the nine sectors of the Blue Economy recognized by the European Commission in the 2024 report, highlighting activities such as offshore wind energy [19]. The Blue Economy is crucial for the future development of European ports, contributing significantly to the European Union's energy transition, supporting decarbonization objectives, and reducing dependence on fossil fuels. Additionally, it fosters sustainable economic growth, creates employment opportunities, and strengthens port competitiveness by integrating clean energy sources. Ports, as centers of logistics and operations, will play a key role in the expansion of these technologies, promoting both the Blue Economy and environmental sustainability.

Port sustainability requires an integrated approach that encompasses economic, social, and environmental dimensions. From an economic perspective, the implementation of renewable energies and more efficient technologies can reduce long-term operational costs and strengthen port competitiveness [18]. ocially, port planning must incorporate community participation and promote activities that generate local employment, seeking to maximize the social benefits of port activities [13]. Moreover, from an environmental perspective, it is crucial to adopt measures that minimize emissions and impacts on marine ecosystems, as well as manage the land-intensive use of port infrastructure. Ports, as significant energy consumers and sources of pollution, must integrate clean technologies and environmental management practices to reduce their ecological footprint [28]. In summary, a sustainable port is one that balances economic efficiency with social benefits and environmental protection, thereby fostering holistic and enduring development. he development of the Blue Economy is fully aligned with European sustainable development policies, such as the

* Corresponding author.
E-mail address: j.vaca@upm.es (J. Vaca-Cabrero).

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Green Deal and the "Fit for 55″ package. The Blue Economy, which includes the Marine Renewable Energy sector, promotes the transition towards a clean energy model in European ports, crucial for reducing carbon emissions and achieving the European Union's decarbonization goals. Initiatives such as offshore wind energy contribute not only to reducing dependence on fossil fuels but also to promoting sustainable economic growth and job creation [19]. orts, considered as logistical and operational hubs, are fundamental to achieving these goals, acting as catalysts for innovation and energy efficiency, supporting the "Fit for 55″ objectives to reduce emissions by 55 % by 2030 [22,29]. Integrating economic, social, and environmental sustainability into port development is essential to enhance competitiveness, minimize environmental impact, and ensure equitable growth that benefits local communities [10]. In this context, European ports are aligned with the commitments of the Green Deal to foster a fair and sustainable transition towards a more resilient and low-carbon future.

The main objective of this research is to identify key sustainability indicators for the development of the Marine Renewable Energy sector within the Blue Economy of Spanish ports using Bayesian networks. The goal is to determine which factors are the most influential from an integrated perspective encompassing economic, social, and environmental dimensions. A secondary objective is to develop a decision-support tool for strategic planning in ports, promoting balanced and sustainable sectoral development. The motivation for this article lies in the need to promote sustainability in a key sector for Europe's energy transition, thereby contributing to meeting climate goals and strengthening the competitiveness of ports as key actors in the Blue Economy.

The article is structured as follows: the "State of the Art" section presents a literature review related to port sustainability, the Marine Renewable Energy sector, and the use of Bayesian networks in sustainability studies. The "Methodology" section describes the employed approach, covering aspects from the selection of the study scope to the construction of the Bayesian model. The "Results and Analysis" section presents the obtained findings and discusses their implications for sustainable sectoral development. Finally, the "Conclusions" highlight the contributions of the research and propose directions for future studies.

2. State of the art

2.1. Port sustainability

Studies on port sustainability provide a comprehensive view of the current state, challenges, and opportunities faced by ports to progress towards more sustainable development. It is identified one of the main challenges as the lack of consistency in measurements and the difficulty of implementing sustainable strategies homogeneously across different regions [28]. Similarly, there are proposals to create a framework based on the United Nations Sustainable Development Goals (SDGs), allowing port sustainability actions and measures to be categorized into environmental, economic, and social domains [2]. However, a major challenge is the limited adoption of sustainable practices due to a lack of resources and clear policies. In the social aspect of sustainability, the importance of involving local communities in the construction of sustainability indicators is highlighted, emphasizing that ports should align with stakeholder priorities to ensure success in sustainable management [37].

Regarding opportunities, there are innovative tools for evaluating port sustainability comprehensively. An example is the application of the End-to-End tool to assess a fishing port, such as the port of Vigo, Spain, demonstrating that the analysis of environmental, economic, and social aspects helps identify key areas for improvement and promote more effective ecological practices [33]. tudies on other facilities closely linked to ports, such as dry ports, also highlight the opportunity to deepen less explored research areas and strengthen collaboration among actors involved in sustainability [6]. All studies converge in concluding that ports have a crucial role in transitioning towards a sustainable future, requiring effective coordination, improvements in indicator measurement, and a holistic approach that integrates all stakeholders in the process.

2.2. Marine renewable energy sector and its implication in ports

Recent studies on integrating marine renewable energies into ports highlight both the challenges and opportunities this transition offers towards port sustainability. From an international perspective on assessing the environmental effects of marine energy development, there is a need to better understand the interactions between these systems and the marine environment to mitigate potential negative impacts [14]. Similarly, the synthesis of the environmental effects of oceanic energy emphasizes the importance of a balanced approach that ensures both energy generation and ecosystem conservation [8]. Additionally, the dimension of marine space-use conflicts must be noted, highlighting that the growing competition for these spaces demands effective spatial planning to avoid conflicts with other sectors like fisheries and tourism [21].

Various studies also address the technical and economic viability of integrating renewable energies into specific ports. It is demonstrate the feasibility of harnessing wave energy to meet part of the energy demand at the port of Valencia, Spain, which not only reduces operational costs but also minimizes carbon emissions [11]. The use of tidal energy is also investigated, showing it can be a sufficient driver to achieve energy self-sufficiency at a port, indicating that harnessing local marine resources can lead to a significant reduction in fossil fuel dependence [32]. In a similar context, the use of marine renewable energy in Middle Eastern ports is examined, highlighting the need to adapt technological solutions to the specific characteristics of each region [24].

In the context of Spain, the recently approved Maritime Spatial Planning Plans (POEMs) represent a fundamental strategic tool for sustainable maritime space management. These plans identify suitable areas for different uses, including marine renewable energy production, facilitating the creation of energy hubs in specific zones. POEMs promote spatial planning that optimizes the use of maritime space, minimizes conflicts with other sectors, and facilitates the integration of marine energy installations. Effective planning is key to transforming maritime areas into strategic points of clean energy generation, supporting both environmental sustainability and economic development of ports and coastal regions [31].

Finally, there are trends in collaborative approaches and technical perspectives for implementing these technologies. Buonomano et al. propose the creation of energy communities in ports, allowing shared production and management of renewable energy, optimizing local resources [9]. Additionally, various technologies such as solar, wind, and tidal energy are evaluated, considering their technical viability and economic profitability, and providing recommendations for ports to reduce their carbon footprint [30]. Collectively, these studies reinforce the idea that transitioning towards sustainable ports should include developing clean technologies and efficiently and collaboratively managing resources to ensure long-term environmental, economic, and social benefits.

2.3. Sustainability in marine renewable energy sector

The integration of marine renewable energy technologies presents significant opportunities and challenges in advancing sustainability across various dimensions. Technologically, these innovations are rapidly evolving, with advancements in wave, tidal, and offshore wind energy improving efficiency and reliability. [23] emphasize that emerging technologies such as hybrid renewable systems and advanced energy storage solutions are essential for enhancing the feasibility and resilience of marine energy projects. Moreover, [15] highlight that sustainable technologies, including eco-friendly materials and adaptive systems for harsh marine environments, play a pivotal role in minimizing ecological impacts while ensuring long-term operability. These technological developments not only support the energy transition but also address critical barriers such as durability and cost-effectiveness in marine applications.

Economically and socially, marine renewable energy has the potential to drive regional development while fostering environmental sustainability. [7] analyze the economic feasibility of such projects, indicating that long-term investments in marine energy reduce dependency on fossil fuels and generate cost savings, despite high initial expenses. [39] underscore that regions like the Mediterranean Sea offer untapped opportunities for marine energy, creating jobs and stimulating local economies. Furthermore, [25] provide a socio-technical assessment, showing that these technologies can enhance energy equity in coastal communities, though they require inclusive decision-making processes to address community concerns and promote equitable benefits distribution.

2.4. Sustainability indicators

Sustainability indicators are fundamental tools for assessing and monitoring the environmental, social, and economic performance of different sectors, such as cities, energy, tourism, and ports. They allow progress towards sustainable development goals to be measured, facilitating informed decision-making aligned with sustainability. These indicators can be classified into several types: environmental indicators that measure impact on the environment, social indicators that evaluate quality of life and equity, and economic indicators that analyze efficiency and economic growth [5].

Sustainability assessment is conducted through various methodologies, such as multicriteria analysis and life cycle assessment, which provide a comprehensive view of performance while emphasizing the importance of evaluating all sustainability dimensions [20]. In the port sector, there are proposals for a framework to report environmental indicators, aiming to harmonize sustainability assessment across ports [35]. he appropriate choice of indicators is crucial for tailoring the assessment to each specific context. An example is the assessment conducted in the Italian port system, which analyzed the economic and environmental efficiency of 13 Italian ports using Data Envelopment Analysis. The conclusion was that only some ports achieve optimal efficiency, while others exhibit inefficiencies. Recommendations include adopting green technologies and improving operational management to balance sustainability and competitiveness ([12]. hese indicators allow progress to be monitored, inform decision-making, and promote transparency. In the port context, these indicators help align port practices with international commitments and allow for the evaluation of port operations' impact on key sustainability dimensions, such as emission reductions and energy efficiency [3]. In summary, sustainability indicators are vital tools for guiding the transition towards more balanced and responsible development across various sectors, particularly the port sector.

2.5. Bayesian networks in sustainability studies

Bayesian Networks (BNs) are probabilistic tools useful for representing dependency relationships between variables and managing uncertainty in complex systems, which has promoted their use in sustainability studies. In sustainable environmental management, BNs are highlighted as a participatory approach that facilitates the integration of knowledge from multiple actors to better understand complex environmental systems, contributing to addressing environmental challenges in a more holistic manner [16].

In the social sustainability domain, BNs are used to evaluate the social impact of infrastructure projects. This approach allows for analyzing different design alternatives and mitigating potential negative effects on communities, ensuring more balanced and sustainable planning [38]. BNs are also applied in the evaluation of watershed sustainability, integrating environmental and socio-economic variables to sustainably manage resources in the Hablehrood river basin [26]. This type of assessment demonstrates the ability of BNs to manage multiple interrelated factors. n supply chain sustainability, multi-level BNs are employed to evaluate the sustainability of a supply network, considering economic, environmental, and social aspects. This allows identifying areas for improvement and conducting comprehensive evaluations in logistics [17]. dditionally, BNs are used to develop a model for assessing the resilience of urban transportation systems, providing a key tool for planning and managing urban mobility in a sustainable and resilient manner [40].

In the renewable energy sector, BNs are used for risk analysis in the wind energy industry, which helps improve the sustainability and reliability of energy systems [1]. Moreover, BNs are applied to explore interrelationships between Sustainable Development Goal 6 (clean water and sanitation) and other goals of the 2030 Agenda, providing a deeper understanding of synergies and trade-offs in policy implementation [34]. n the port context, BNs have been applied to classify and predict port variables, improving port management and operational efficiency. The results demonstrate the effectiveness of this approach in strategic decision-making in the port domain [36].

In summary, BNs are fundamental tools in sustainability evaluation and planning, allowing the integration of various variables and the management of uncertainty in decision-making processes to advance towards more sustainable development in multiple sectors.

2.6. Research gap

The literature review identifies a significant gap in studies on port sustainability and marine renewable energy. Although there is considerable focus on environmental sustainability and energy efficiency in ports, there is a lack of analysis that integrates environmental, economic, and social dimensions. Additionally, studies tend to focus on port sustainability solely within the infrastructure scope, without addressing the crucial role ports can play as platforms for developing offshore renewable energies.

This research seeks to address these gaps by using Bayesian Networks to identify and analyze the most influential sustainability indicators for developing marine renewable energies as a sector of the Blue Economy. The proposed approach considers ports as true centers for driving offshore energy, assessing their capacities not only from an environmental perspective but also considering socio-economic impacts. This way, the study provides a more balanced and holistic analysis, highlighting the importance of ports in transitioning to a sustainable energy model that also generates economic and social opportunities at both local and regional/national levels.

3. Methodology

In this chapter, the phases followed in the research are presented. These phases are schematically outlined in Fig. 1.

3.1. Phase 0: research design

The design of this research is descriptive and exploratory. The method employed is suitable for the objective since it describes the interrelations between environmental, social, and economic sustainability indicators, and explores which of them are most influential in the development of the Marine Renewable Energy sector in Spanish ports. This approach allows not only the understanding of existing patterns but also the identification and prediction of new opportunities to enhance the sustainable development of the Blue Economy.

3.2. Phase 1: selection of study scope

In this research, the study scope includes all 28 port authorities of the

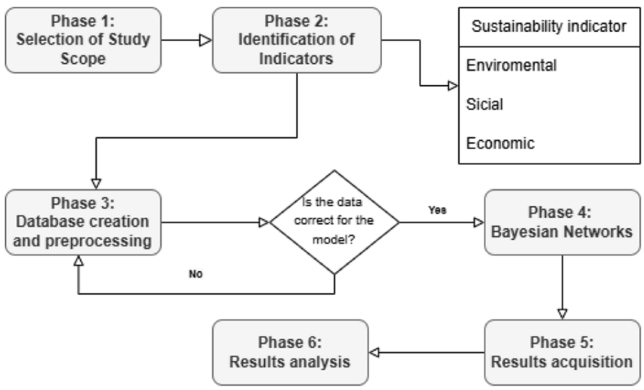

Fig. 1. Researching chart flow. Source: own elaboration.

Spanish system, ensuring sufficient representativeness and relevance for the development of the Marine Renewable Energy sector. By including all port authorities, ports from various coastal regions of Spain are represented, thus reflecting the heterogeneity of the Spanish port system. Different types of port districts with their infrastructures are also represented, ensuring the versatility and suitability of facilities dedicated to aspects closely related to marine renewable energies, such as wind and tidal energy.

3.3. *Phase 2: identification of indicators*

As a necessary step to construct the Bayesian network, environmental, social, and economic sustainability indicators were identified and selected. These indicators include aspects such as local employment creation, investments in environmental characterization, number of jobs in the port, etc. The selection of these indicators was based on official sources from the public entity Puertos del Estado, such as port sustainability and economic reports, all of this information is open data.

3.4. *Phase 3: database creation and preprocessing*

In this phase, the time series of indicator data on an annual scale was collected. Next, data preprocessing was carried out to facilitate model application:

- Encoding categorical data into numerical form.
- Normalizing values.
- Discretizing values into five intervals.

3.5. *Phase 4: redes bayesianas*

3.5.1. *Definition and justification*

Bayesian networks were chosen as the main tool due to their ability to model dependency relationships between variables and handle uncertainty, which is crucial in this type of study where multiple factors are interrelated [36]. This technique allows the identification of conditional relationships between different indicators and the evaluation of which are most influential in the development of the Marine Renewable Energy sector within the Blue Economy. These probabilistic networks are based on Bayes' theorem. The general formula for calculating the probability of a series of variables (nodes) is as follows (Formula (1)):

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P(X_i | Pa(X_i)) \tag{1}$$

Where:

- $X_1, X_2, \ldots, X_n$ are the variables of the Bayesian network.
- $P(X_i|Pa(X_i))$ represents the conditional probability of variable X_i, given its parent set $Pa(X_i)$, which are the nodes that have a direct connection to X_i.

3.5.2. *Model construction*

The Bayesian network model was built using the pgmpy software [4], Python library specialized in probabilistic networks. A network structure was established that includes the selected indicators as nodes, and the connections between these represent dependency relationships. To define the structure, techniques based on expert knowledge and analysis of historical data from the selected ports were used.

3.5.3. *Phase 5: results acquisition*

The initial results obtained from the model graphically displayed all possible probabilistic relationships between the nodes. The network was subsequently pruned in several iterations using expert criteria to discard weak relationships, resulting in the final network.

3.5.4. *Phase 6: results and analysis*

In this final phase of the research, the final results were obtained and analyzed. The data analysis included descriptive statistical techniques to determine the relationships between the indicators. This approach allowed the identification of key indicators and provided practical recommendations for optimizing efforts in the development of the Marine Renewable Energy sector from a sustainable perspective.

4. Results and analysis of the results

The results begin by applying the Bayesian network method to the database. Initially, there were 49 indicators (variables) used to run the model, and after the first preprocessing and analysis, 15 variables with 46 interdependencies were obtained (Fig. 2).

In Fig. 2, several cross-connections between nodes can be observed, indicating a complexity within the Bayesian network. This can result from strong relationships or mutual dependencies between some variables. Cross-connections often suggest that multiple nodes are correlated and influence each other, making interpretation difficult without a clear hierarchy.

Therefore, it is evident that pruning the network under expert criteria and establishing a hierarchical structure are necessary, where the upper level includes the network parents and the lower levels contain the child nodes and their interrelationships. This is complemented with the use of an adjacency matrix to identify the less significant interconnections. The main objective is to simplify the network structure, improving interpretability and efficiency without sacrificing predictive capability. The adjacency matrix helps visualize weaker or redundant connections, facilitating an informed pruning. This reduces

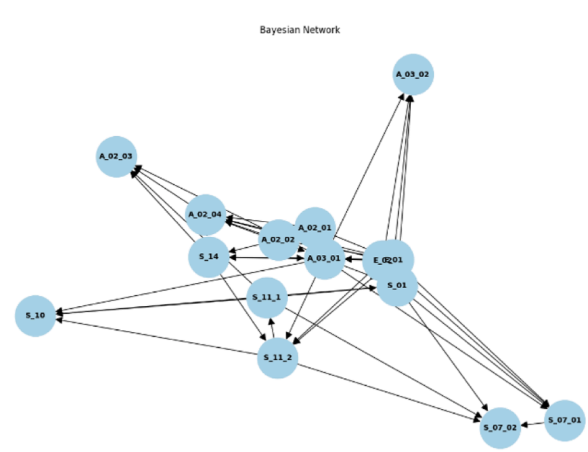

Fig. 2. Original Bayesian Network. Source: own elaboration.

the model's complexity by removing arcs and nodes that do not significantly contribute to understanding or predicting variable behavior. The result is a more manageable network with a reduced risk of overfitting, improved computational performance, and a clearer structure that highlights key relationships within the modeled system.

After several iterations of pruning and improving the graphical interpretation of the model, the transition from a complex and difficult-to-interpret network (Fig. 3) to a manageable one that justifies decision-making with fewer variables (Fig. 4) is achieved.

The hierarchical Bayesian network obtained in Fig. 4 shows a clearer and simpler structure after pruning. Key nodes, such as E_02 and A_02_02, appear as influential variables with multiple connections to other nodes, suggesting their relevance within the network; they are categorized as the network's parents. This hierarchical organization facilitates the interpretation of parent-child relationships (from higher to lower levels) and reduces model complexity, making it more evident how dependencies flow through the structure. Nodes with multiple parents, such as A_02_04 and S_14, reflect the existence of multiple factors influencing these variables. The thickness of relationship lines also deserves attention, as greater thickness indicates a stronger dependence between variables.

Comparing the evolution from Fig. 3–Fig. 4, it is clear that many relationships have been eliminated without any loss of information, allowing the focus on the most relevant connections and improving efficiency, achieving a balance between model simplicity and the preservation of important relationships.

Next, the resulting variables from the final pruning of the model are analyzed. Table 1 shows the final seven indicators, ordered from highest to lowest weight in the network..

The results presented in Table 1 highlight a set of key variables that characterize the sustainable development of the marine renewable energy sector within the blue economy of ports in the Spanish port system. Specifically, economic, environmental, and social aspects are identified as playing a fundamental role in the sector's evolution. Economic variables (2 out of 7), such as "Evolution of total investments in accruals" and "Fixed assets in accruals," reflect the importance of consistent and efficient infrastructure investment, which is essential to support the sector's growth. These investments facilitate the modernization and adaptation of port areas and the implementation of technologies that enable the integration of renewable energies.

On the other hand, environmental variables (4 out of 7) and social variables (1 out of 7) underline the need for a balanced approach between economic growth and environmental and social responsibility. Investment in environmental characterization helps mitigate the negative impacts of port activities. Additionally, the "annual accident frequency rate" is a key indicator in the social dimension, as occupational safety in projects such as offshore energy must be a priority for sustainable development. Overall, these results emphasize that the development of the marine renewable energy sector depends not only on adequate economic investment but also on proactive environmental management and the implementation of effective occupational safety measures.

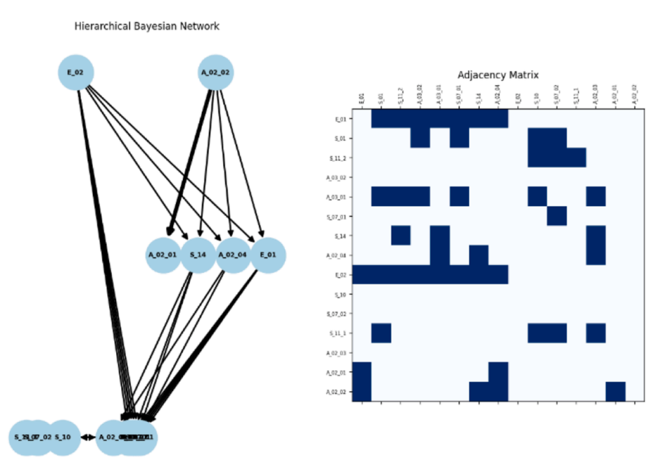

Fig. 3. Original Hierarchical Bayesian Network (left) and Adjacency matrix (right) original. Source: own elaboration.

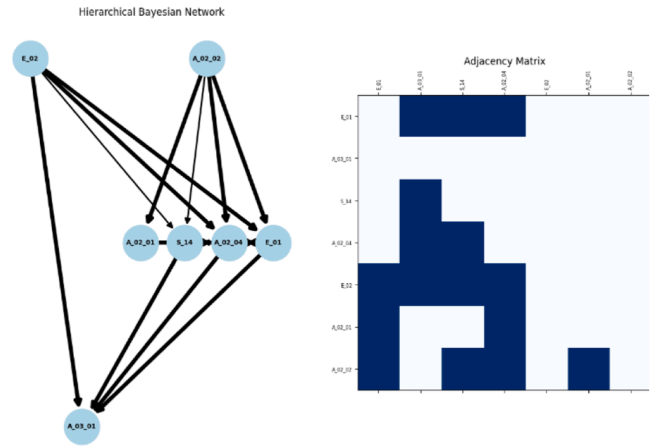

Fig. 4. Pruned Hierarchical Bayesian Network (left) and Adjacency matrix (right) original. Source: own elaboration.

5. Conclusion

5.1. Main findings

The conclusions of this research demonstrate that the main objective has been met: identifying, through the use of Bayesian networks, the most determining indicators for the sustainable development of the Marine Renewable Energy sector within the blue economy of ports in the Spanish port system, which are mainly the Evolution of Total Investments and Economic Efforts in Environmental Characterization.

The obtained results provide evidence of the essential elements that must be strengthened to ensure the sustainable development of marine renewable energies in the context of Spanish ports. They offer a solid foundation for strategic decision-making aimed at promoting the balanced growth of the blue economy.

The applicability of the developed Bayesian model is demonstrated in its ability to provide a comprehensive and quantitative view of the interrelationships between different variables. This probabilistic tool not only allows for the analysis of direct relationships between sustainability indicators but also infers indirect dependencies and evaluates the potential impact of various strategic decisions. Its implementation in port management will facilitate planning and prioritization of investments in critical areas, optimizing available resources, and improving responsiveness to environmental and socio-economic challenges that may arise during the energy transition process.

5.2. Practical implications

One of the novel aspects of this work lies in the application of Bayesian networks as a modelling tool for the sustainability of the marine renewable energy sector. It facilitates decision-making under uncertainty, a common scenario in resource management in the port environment. The ability of Bayesian networks to represent and quantify the dependency relationships between variables offers a significant advantage over more traditional approaches, providing a more dynamic and flexible analysis.

Additionally, the innovative use of specific sustainability indicators for the Spanish port system in the context of the development of the Blue Economy is another added value of this research. By focusing on

Table 1
Results and characterization of the predominant variables obtained in the Bayesian network model.

Code	*Category*	*Variable*	*Justification of the variable*
E_02	Economic	Evolution of total investments in accruals	It reflects the financial capacity and availability of resources for the development of infrastructures and technologies in marine renewable energy, being essential to promote the sustainable growth of the sector.
A_02–02	Environmental	% of investment in environmental characterization with respect to the total	Investment in environmental characterization ensures a detailed assessment of the marine environment and minimizes environmental impacts by ensuring the sustainability of renewable energy development.
A_02_01	Environmental	Investment in environmental characterization	It derives from indicator A_02_02, directly indicating the resources dedicated to environmental characterization.
E_01	Economic	Evolution of property, plant and equipment in accruals	The development of the sector depends on a robust and modern port infrastructure. This variable reflects investment in tangible assets that are key to supporting marine renewable energy facilities and their growth in the port.
A_02_04	Environmental	% of expenditure on environmental characterization	Controlling expenditure on environmental characterization is important to ensure that resources are allocated sufficiently and appropriately to protect the marine environment and ensure the viability of renewable energy projects.
S_14	Social	Annual accident frequency rate	Workplace accidents on offshore projects are a major risk, and monitoring the frequency index is essential to improve safety and protect the workers involved.
A_03_01	Environmental	Expenses in € in cleaning of port areas	The cleanliness of the port is crucial to maintain a healthy environment and minimize the negative effects of industrial activities, supporting a sustainable development of marine renewable energy projects.

indicators that reflect the specific realities of ports, this study provides an accurate evaluation of how renewable energy activities can be developed more sustainably. The selected economic, social, and environmental indicators provide a framework that integrates the triple sustainability balance and allows ports to identify key areas of improvement, such as investment efforts, environmental characterization, and worker safety.

Thus, the importance of an integrated and balanced vision of port development is established, encompassing economic, environmental, and social aspects, closing the identified research gap outlined in the state of the art.

5.3. Limitations and prospective

This research has faced some limitations mainly related to data acquisition. The lack of data homogeneity or the large volume of mainly environmental indicator data made it necessary to preprocess the database to adjust it as closely as possible to the model's input needs. In terms of future directions, the implementation of this model in other international port contexts and in a greater number of Blue Economy sectors is proposed. To add more value to the research, it would be optimal to promote the measurement and integration of more dynamic, real-time indicators that allow the evaluation of the impact of specific policies and actions over time with greater precision. It would also be appropriate to generate an open data repository of indicators for future research.

The analysis conducted reveals that the marine renewable energy sector depends not only on adequate economic investment but also on proactive environmental management and the implementation of effective occupational safety measures. The use of Bayesian networks has enabled a deep analysis of these interrelationships, and the results obtained offer guidance for decision-making in planning the sustainable development of the sector. It is hoped that this approach can be replicated in other contexts and become a useful tool to enhance competitiveness, improve efficiency, and ensure a fair and sustainable transition towards a low-carbon future in European ports.

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CRediT authorship contribution statement

Javier Vaca-Cabrero: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Nicoletta González-Cancelas:** Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Alberto Camarero-Orive:** Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Data availability

The authors do not have permission to share data.

References

[1] T. Adedipe, M. Shafiee, E. Zio, Bayesian network modelling for the wind energy industry: An overview, Reliab. Eng. Syst. Saf. 202 (2020) 107053.
[2] A.S. Alamoush, F. Ballini, A.I. Ölçer, Revisiting port sustainability as a foundation for the implementation of the United Nations Sustainable Development Goals (UN SDGs), Journal of Shipping and Trade 6 (1) (2021) 19, https://doi.org/10.1186/s41072-021-00101-6.
[3] A.S. Alamoush, F. Ballini, A.I. Ölçer, Revisiting port sustainability as a foundation for the implementation of the United Nations Sustainable Development Goals (UN SDGs), Journal of Shipping and Trade 6 (1) (2021) 19, https://doi.org/10.1186/s41072-021-00101-6.
[4] A. Ankan, J. Textor, pgmpy: a Python Toolkit for Bayesian Networks, En Journal Of Machine Learning Research (2024) 1–8. Versión 0.1.26, Número 25[Python], https://github.com/pgmpy/pgmpy (Obra original publicada en 2013).
[5] S. Bell, S. Morse, Sustainability indicators: Measuring the immeasurable? Routledge, 2012. https://www.taylorfrancis.com/books/mono/10.4324/9781849772723/sustainability-indicators-stephen-morse-simon-bell.
[6] Z.T. Beyene, S.P. Nadeem, M.E. Jaleta, A. Kreie, Research trends in dry port sustainability: a bibliometric analysis, Sustainability. 16 (1) (2023) 263.
[7] M.A. Bhuiyan, P. Hu, V. Khare, Y. Hamaguchi, B.K. Thakur, M.K. Rahman, Economic feasibility of marine renewable energy, Front. Mar. Sci. 9 (2022) 988513.
[8] G.W. Boehlert, A.B. Gill, Environmental and ecological effects of ocean renewable energy development: a current synthesis, Oceanography 23 (2) (2010) 68–81.
[9] A. Buonomano, G.F. Giuzio, R. Maka, A. Palombo, G. Russo, Empowering sea ports with renewable energy under the enabling framework of the energy communities, Energy Convers. Manage 314 (2024) 118693.
[10] A. Caliskan, Seaports participation in enhancing the sustainable development goals, J. Clean. Prod. 379 (2022) 134715.
[11] R. Cascajo, E. García, E. Quiles, A. Correcher, F. Morant, Integration of marine wave energy converters into seaports: a case study in the port of Valencia, Energies. (Basel) 12 (5) (2019) 787.
[12] R. Castellano, M. Ferretti, G. Musella, M. Risitano, Evaluating the economic and environmental efficiency of ports: Evidence from Italy, J. Clean. Prod. 271 (2020) 122560.
[13] B. Cavallo, L. D'Apuzzo, M. Squillante, A multi-criteria decision making method for sustainable development of Naples port city-area, Qual. Quant. 49 (4) (2015) 1647–1659, https://doi.org/10.1007/s11135-014-0077-9.
[14] A.E. Copping, L.G. Hemery, H. Viehman, A.C. Seitz, G.J. Staines, D.J. Hasselman, Are fish in danger? A review of environmental effects of marine renewable energy on fishes, Biol. Conserv. 262 (2021) 109297.
[15] Y. Cui, H. Zhao, Marine renewable energy project: The environmental implication and sustainable technology, Ocean. Coast. Manage 232 (2023) 106415.
[16] M. Düspohl, S. Frank, P. Döll, A review of Bayesian networks as a participatory modeling approach in support of sustainable environmental management, J. Sustain. Dev. 5 (12) (2012) 1–18.
[17] S. El Amrani, N.U.I. Hossain, S. Karam, R. Jaradat, F. Nur, M.A. Hamilton, J. Ma, Modelling and assessing sustainability of a supply chain network leveraging multi Echelon Bayesian Network, J. Clean. Prod. 302 (2021) 126855.
[18] H.M. Elnajjar, A.S. Shehata, A.A. Elbatran, M.F. Shehadeh, Experimental and techno-economic feasibility analysis of renewable energy technologies for Jabel Ali Port in UAE, Energy Reports 7 (2021) 116–136.
[19] European Commission, Joint Research Centre (European Commission), The EU Blue Economy Report 2024, Publications Office of the European Union, 2024. https://data.europa.eu/doi/10.2771/186064.
[20] I. Gunnarsdóttir, B. Davidsdottir, E. Worrell, S. Sigurgeirsdóttir, Review of indicators for sustainable energy development, Renewable and Sustainable Energy Reviews 133 (2020) 110294.
[21] Harte, M.J., Campbell, H.V., & Webster, J. (2010). Looking for safe harbor in a crowded sea: Coastal space use conflict and marine renewable energy development. https://ir.library.oregonstate.edu/concern/defaults/ms35t9341.
[22] Hendriks, C., & Gooyert, V. de. (2023). Towards sustainable port areas: Dynamics of industrial decarbonization and the role of port authorities. https://repository.ubn.ru.nl/bitstream/handle/2066/291818/291818.pdf.
[23] A. Hussain, S.M. Arif, M. Aslam, Emerging renewable and sustainable energy technologies: state of the art, Renewable and sustainable energy reviews 71 (2017) 12–28.
[24] D.R. Kandiyil, Use of Marine Renewable Energy in Ports of Middle East: a Step Toward Sustainable Ports, En E. Heggy, V. Bermudez, & M. Vermeersch (Eds.). Sustainable Energy-Water-Environment Nexus in Deserts, Springer International Publishing, 2022, pp. 349–356, https://doi.org/10.1007/978-3-030-76081-6_42.
[25] K. Kazimierczuk, C. Henderson, K. Duffy, S. Hanif, S. Bhattacharya, S. Biswas, E. Jacroux, D. Preziuso, D. Wu, D. Bhatnagar, A socio-technical assessment of marine renewable energy potential in coastal communities, Energy Res. Soc. Sci. 100 (2023) 103098.
[26] A.R. Keshtkar, A. Salajegheh, A. Sadoddin, M.G. Allan, Application of Bayesian networks for sustainability assessment in catchment modeling and management (Case study: the Hablehrood river catchment), Ecol. Modell. 268 (2013) 48–54.
[27] K.H. Lee, J. Noh, J.S. Khim, The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities, Environ. Int. 137 (2020) 105528.
[28] S. Lim, S. Pettit, W. Abouarghoub, A. Beresford, Port sustainability and performance: a systematic literature review, Transportation Research Part D: Transport and Environment 72 (2019) 47–64, https://doi.org/10.1016/j.trd.2019.04.009.
[29] T. Notteboom, H. Haralambides, Seaports as green hydrogen hubs: Advances, opportunities and challenges in Europe, Maritime Economics & Logistics 25 (1) (2023) 1–27, https://doi.org/10.1057/s41278-023-00253-1.
[30] M. Parhamfar, I. Sadeghkhani, A.M. Adeli, Towards the application of renewable energy technologies in green ports: Technical and economic perspectives, IET Renewable Power Generation 17 (12) (2023) 3120–3132.
[31] PLANES DE ORDENACIÓN DEL ESPACIO MARÍTIMO. 2025 (s. f.).
[32] V. Ramos, R. Carballo, M. Álvarez, M. Sánchez, G. Iglesias, A port towards energy self-sufficiency using tidal stream power, Energy 71 (2014) 432–444.
[33] E. Ramos Velasco, N. González-Cancelas, A. Camarero Orive, D Díaz-Gutiérrez, Green Ports Analysis Using an End-to-End Tool Application in the Fishing Port of Vigo, J. Mar. Sci. Eng. 10 (12) (2022), https://doi.org/10.3390/jmse10121959. Article 12.
[34] D. Requejo-Castro, R. Giné-Garriga, A. Pérez-Foguet, Data-driven Bayesian network modelling to explore the relationships between SDG 6 and the 2030 Agenda, Science of the total environment 710 (2020) 136014.
[35] V. Rodrigues, M. Russo, S. Sorte, J. Reis, K. Oliveira, A.L. Dionísio, A. Monteiro, M. Lopes, Harmonizing sustainability assessment in seaports: a common framework for reporting environmental performance indicators, Ocean. Coast. Manage 202 (2021) 105514.
[36] B.M. Serrano, N. González-Cancelas, F. Soler-Flores, A. Camarero-Orive, Classification and prediction of port variables using Bayesian Networks, Transp. Policy. (Oxf) 67 (2018) 57–66.
[37] T.A. Shiau, C.C. Chuang, Social construction of port sustainability indicators: a case study of Keelung Port, Maritime Policy & Management 42 (1) (2015) 26–42, https://doi.org/10.1080/03088839.2013.863436.
[38] L.A. Sierra, V. Yepes, T. García-Segura, E. Pellicer, Bayesian network method for decision-making about the social sustainability of infrastructure projects, J. Clean. Prod. 176 (2018) 521–534.
[39] T.H. Soukissian, D. Denaxa, F. Karathanasi, A. Prospathopoulos, K. Sarantakos, A. Iona, K. Georgantas, S. Mavrakos, Marine renewable energy in the Mediterranean Sea: Status and perspectives, Energies. (Basel) 10 (10) (2017) 1512.
[40] J. Tang, H. Heinimann, K. Han, H. Luo, B. Zhong, Evaluating resilience in urban transportation systems for sustainability: a systems-based Bayesian network model, Transportation Research Part C: Emerging Technologies 121 (2020) 102840.
[41] J. Vaca Cabrero, C.P. Gómez Garach, A. Camarero Orive, N González-Cancelas, Evaluation of the Implementation of the Dimensions of the Blue Economy in Spanish Ports, J. Mar. Sci. Eng. 12 (2) (2024) 222.