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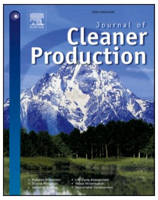

An integrated PROMETHEE II-Roadmap model: Application to the recovery of residual agroforestry biomass in Portugal

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ABSTRACT

Rural fires are currently one of the main global disasters, and Portugal is among the countries that have suffered from them for decades. These fires pose economic, environmental, and social threats to the country. A primary cause of rural fires is the burning of biomass to clear agroforestry residues. Thus, combating rural fires requires more effective forest management, particularly the removal of forest residues that serve as fuel. These residues, also known as biomass, have significant potential for energy production and biofuel use. This paper proposes a model that integrates the PROMETHEE decision-making method with the roadmapping. This proposed model includes 7 steps, including the planning of the roadmap, the definition of the decision problem, gathering information and building the roadmap. The proposed model was applied to develop a roadmap proposal for the recovery of surplus agroforestry biomass in Portugal, identifying the most emerging conversion technologies in the national context. With the roadmap developed, it was possible to understand that the recovery of surplus agroforestry biomass in Portugal involves several sectors. The energy sector is one of those that can benefit from the recovery of leftover agroforestry biomass, both from the point of view of carbon neutrality and energy independence. Forestry management is another of the great advantages of recovering leftover forestry biomass and, consequently, reducing the number of fires. In the context of recovery, combustion is the most widely used technology for producing energy or heat. The technology identified as most emerging in the upcoming years is gasification. Investment in scientific research is essential for the success of this sector, as is the development of public incentive policies and more engagement from all stakeholders. This paper conclude that valorizing agroforestry residues can reduce rural fire risks while promoting energy independence, sustainable regional development, and innovation in Portugal.

1. Introduction

In recent years, Portugal and the world have been affected by rural fires. In 2022 alone, the area burned in the southeast of Portugal was 2 times higher than the average area burned between 2001 and 2021, while in the northwest this factor doubles to 4 times higher than the average area burnt in the previous 20 years (Rodrigues et al., 2023b). It is therefore essential to take measures to reduce rural fires. In Portugal, the main cause of rural fires, occurring more than half of the time, is the use of fire motivated by the disposal of agroforestry residues (Moretti

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et al., 2021). In Portugal, around 38% of the national territory is covered by forests (A Biomassa em Portugal, 2021). Effective forest management is therefore essential if the number of forest fires is to be reduced. In this sense, the valorization of residual agroforestry biomass (RAFB) can be seen as an opportunity to reduce the number of rural fires in Portugal and as an enabler of forest conservation (Ferreira et al., 2015). In this sense, the novelty of the paper is the relationship between the prevention of forest fires and the use of agroforest residues. Biomass is considered any type of material of biological origin, whether it comes from plants, animals, or microorganisms that exist in different ecosystems on planet Earth (Braghiroli and Passarini, 2020). The different types of biomass include agricultural waste like corn, wheat, sugar cane, and soya harvests, among others; forestry waste; animal manure and municipal solid waste. There are different valorization technologies for biomass, including physicochemical, thermochemical, and biological technologies (Bonechi et al., 2017). Different technologies are used for different types of biomass and are used to produce different products.

Besides contributing to a more efficient forest management, the valorization of RAFB can also help to fight one of the biggest problems of recent decades - energy dependency (Naveen Kumar and Senthilkumar, 2020). It is known that in the future the traditional sources of energy, that come from fossil fuels, will run out and that carbon dioxide emissions are increasing every year, largely due to high energy consumption (Abas et al., 2015). Concern for the environment and future generations has led to the development of policies to combat the use of fossil fuels. In the Paris Agreement in 2015, 55 countries, representing 55% of the world's total emissions, committed themselves to limiting global warming and reducing emissions, reaching carbon neutrality by 2050 and reducing its value by 55 % by 2030 (The Paris Agreement - Publication | UNFCCC, n.d.). This requires the integration of various renewable alternatives in energy production. Biomass has emerged around the world as a renewable alternative in the energy sector, which can help reduce dependence on fossil fuels. When used in a sustainable way, biomass can help in the energy crises and be a good asset in terms of reduction of emissions, through its use in energy production and also when the reduction of rural fires is considered (Kabeyi and Olanrewaju, 2022). In Portugal, given the availability of agroforestry residues, motivated by its forestry dimension, the valorization of RAFB has been gaining a relevant role in the country. Currently, agroforestry biomass is mostly valorized through combustion, where the biomass is transformed into electricity or heat, both at residential, industrial, and commercial levels (Ferreira et al., 2017). Recently, some investment has been made in terms of research and development (R&D) to expand the valorization technologies used. Despite all the advantages that the valorization of RAFB can bring, several challenges need to be overcome for it to be a success, including supply chain efficiency, collaboration between the different stakeholders, and the reduction of associated costs (Singhvi and Gokhale, 2019). In this this paper a proposed roadmap for the use of RAFB in Portugal is developed. Roadmaps are tools used for strategic planning. The process of technological roadmapping is a technique that has been growing in recent decades and has been commonly used for strategic planning, as well as aligning technology with the general objectives of companies, governments, or academia (Kostoff and Schaller, 2001). Traditional technology roadmaps are a type of graphical tool that aids in decision-making, helping in the exploration and communication of linkages that exist between markets, products, technologies, and resources throughout time. They also forecast future developments in technology. Roadmaps aim to present the current state of a technology, forecast its future state, and determine strategies for achieving the forecasts made (Amer and Daim, 2010; Matani et al., 2019). This paper aims to develop a model that combines the MCDM method PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) with the roadmapping technique. The proposed model makes it possible to increase the robustness of roadmap construction by adding a mathematical component to a process that until now has been very limited to conventional descriptive strategies that answer "when" and "how" questions. Few articles have been found in the literature that integrate the roadmapping process with any MCDM method, at least from the perspective of a structured roadmap (Jeon et al., 2011; Lee et al., 2011; Matani et al., 2019). This paper aims to contribute to the extension of literature in this topic, providing for the first time a method that integrates the MCDM method PROMETHEE with the roadmapping. The proposed model is very adjustable and can be used in several fields. In this paper, the proposed model is used to develop a roadmap for the valorization of RAFB in Portugal.

In this context, the objectives of this paper are: 1) Understand and characterize agroforestry biomass; the valorization techniques used, and the products obtained from it through a literature review; 2) Propose a structured model that integrates the MCDM method PROMETHEE with the roadmapping technique, which can be used to build roadmaps; 3) Application of the proposed model in the specific context of valorization of RAFB in Portugal.

2. Literature review

2.1. Agroforestry Biomass

The biodegradable portion of biologically derived products and waste from forestry and agriculture, comprising plant, animal, and microbe materials as well as biologically derived industrial and municipal waste, is known as biomass (Braghiroli and Passarini, 2020; Directive (EU) 2018/2001 of the European Parliament and of the Council of December 11, 2018 - on the promotion of the use of energy from renewable sources, n.d.). The main composition of biomass from terrestrial plant is organic material such as cellulose, hemicellulose, and lignin, as well as proteins, lipids, and other organic compounds. This biomass can be divided into lignocellulosic biomass and non-lignocellulosic biomass (Braghiroli and Passarini, 2020). Lignocellulosic materials are composed of hemicellulose, between 25% and 35%, cellulose, between 4% and 50% and lignin, between 15% and 20% (Kumar et al., 2015). Whereas non-lignocellulosic materials are mainly composed of low molecular weight cytoplasm and structural components such as sugar, lipids, and proteins. Forest biomass, which includes woody resources, is essentially composed of lignocellulosic material (Kumar et al., 2015). Biomass derived from forestry, agriculture, or a combination of livestock and agriculture is referred to as agroforestry biomass. One of the most important types of biomass on a global scale is agroforestry biomass and it should be considered when developing strategies to combat climate change (Casau et al., 2022). Agricultural biomass refers to a broad category of biomass from agriculture. Agricultural waste can be defined as primary or secondary, depending on its origin. Primary wastes are the solid plant residues that remain on fields after harvesting or pruning, as well as animal manure. Secondary by-products are those discarded during a processing stage, such as olive pits or marc and walnut shells (Statistical Report, n.d.). Agricultural wastes hold significant potential as a raw material for the burgeoning bioenergy sector and the EU bioeconomy (Chandel et al., 2020), and their effective utilization can play an important role in driving rural development and formulating strategies for climate change mitigation (Duque-Acevedo et al., 2020). However, this potential is presently not fully tapped, primarily because of logistical challenges and insufficient incentives (Carvalho et al., 2020), and addressing these issues could unlock their considerable value and contribute meaningfully to these critical areas (Dey et al., 2021; Faaij, 2022). For example, only a small portion of wheat, corn, and rice crop residues is utilized to produce bioethanol production or animal fodder, all over the world, the rest is discarded or burned in the fields (Koul et al., 2022). The forest residues can be produced from direct forest exploitation as well as the wood processing industry. When compared to the residues from the wood processing industry, the forest residues have a heterogeneous composition due to the presence of branches, leaves, tops, and bark (Braghiroli and Passarini, 2020).

2.2. Biomass valorization

The oldest source of energy used by human, first used with the discovery of fire, is biomass (Abbasi et al., 2011). By the middle of the 19th century, biomass accounted for 85 % of the world's energy consumption. Prior to this date, it was essentially the only source of energy used. With the Industrial Revolution and the century's passage, the use of coal grew to account for 50 % of the world's energy consumption. From the second half of the 19th century, oil and gas became the dominant energy sources (Goldemberg, 2009). Nowadays, biomass can be considered an asset in terms of energy transition and carbon neutrality, because it has several unique characteristics, such as its reserves abundance, low emission level, and the potential of high application (Antar et al., 2021; Kabeyi and Olanrewaju, 2022; Wang et al., 2023; Zhang and Chen, 2022). A study performed in China shows that biomass can be a good asset in energy transition in China as it can reduces its ecological footprint (Wang et al., 2023).

The production of biofuels has increased globally. In 2018, the equivalent of 95 million tons of oil was produced in biofuels, with North America, Central and South America, and Europe being the largest contributors to this figure (Zhang et al., 2020).

Several technologies can be used to convert biomass into value-added products (Casau et al., 2022). The choice of conversion technology depends on several factors, such as the conversion's goal, the available technologies, and their state of maturity, as well as the associated environmental impacts. There are 3 main conversion technologies of biomass: physical-chemical conversion, thermochemical conversion, and biological conversion (Casau et al., 2022; Goldemberg, 2009).

2.2.1. Physical-chemical conversion

Commonly, the physical-chemical conversion is used as a pretreatment that precedes other conversion techniques. Physical-chemical conversion includes reducing the size of the biomass and homogenizing it, as well as the drying, densification, or fractionation of the solvent (Casau et al., 2022). These techniques increase the density of the biomass and reduce its size, and are essential to the efficiency of the supply chain since they enable more efficient transportation logistics, increase storage capacity and improved combustion qualities when comparing to raw biomass (Bajwa et al., 2018; Casau et al., 2022). The densification process allows the homogenization of lignocellulosic biomass, which is important to obtain uniform physical properties, such as, size, shape, density, and durability (Casau et al., 2022; Tumuluru et al., 2011). Diverse densification systems (e.g., pellet mill, briquette press, etc.) are used to produce a homogenized solid commodity for energy conversion (Casau et al., 2022). The pretreatment of lignocellulosic biomass with organic solvents has been performed for decades, and several solvents have been studied to isolate different components from biomass such as cellulose, lignin and hemicellulose (Casau et al., 2022). Pellets, briquettes and logs are three of the products obtained through physical-chemical techniques.

2.2.2. Thermochemical conversion

Thermochemical conversion technologies are used to produce energy and heat (Faaij, 2006). In thermochemical conversion technologies, biomass is subjected to an environment poor or without oxygen where the temperature is adjusted considering the process. These processes, cause the biomass structural changes, improving its energy properties, increasing its hydrophobicity and its resistance to biotic and abiotic agents, and allowing the biomass to be ground more easily, thereby facilitating the physical storage of biomass (Nunes et al., 2021a). Thermochemical conversion technologies for biomass include combustion, torrefaction, pyrolysis, liquefaction, and gasification (Casau et al., 2022).

Combustion involves burning biomass in a process of complete oxidation, which produces heat, carbon dioxide, water, and ash. This process is used in heating and electricity generation systems. Direct combustion is the oldest technique for using biomass (Casau et al., 2022; Demirbas, 2004).

Torrefaction involves heating the biomass to relatively low temperatures, between 200 °C and 300 °C. During the process the biomass loses water and volatile components, resulting in a drier, lighter material with greater energy density. It is possible to improve the physical properties of the biomass, such as shape, size, moisture and granulation through torrefaction (Shankar Tumuluru et al., 2011).

The **pyrolysis** process is similar to torrefaction, but in this case, the heating temperature is higher (Uslu et al., 2008). The pyrolysis process can be divided into three main categories: Slow pyrolysis, intermediate pyrolysis, and fast pyrolysis. These processes have different reaction temperatures, heating rates, feedstock sizes and residence times (Jouhara et al., 2018). The information regarding each process is presented in Table 1. As it is possible to see in Table 1, the operating conditions have a strong impact on the products formed through pyrolysis.

Direct liquefaction can be used to convert biomass into liquid fuels. This process is conducted in the presence of a solvent, usually water, that acts as a catalyst for the reaction. The conversion takes place in a high-temperature and high-pressure water environment, where the polymer structure of the biomass is broken to produce a liquid when mixed with water, produces bio-oil (Gollakota et al., 2018).

Gasification involves the conversion of biomass into gas. During the process, the biomass is converted into small quantities of solid, bio-oil, and large quantities of gaseous products such as syngas, hydrogen, water, and gaseous hydrocarbons. This process takes place in gasifiers where the gasifying agent content is controlled and a high temperature, which can reach 900 °C, is maintained (Casau et al., 2022; Gu et al., 2019).

2.2.3. Biological conversion

Biological conversion technologies include anaerobic digestion and fermentation and are mainly used for the production of transport fuels (Faaij, 2006). One of the challenges of biological conversion is its low efficiency (Casau et al., 2022). In **Anaerobic digestion,** biomass is exposed to an oxygen-free environment in the presence of various groups of microorganisms. These microorganisms are responsible for breaking down the biomass into simpler substances and thus producing biogas. This process is suitable for the conversion of non-sterile, diverse, and complex raw materials such as food waste, industrial wastewater, and organic animal manure. Lignocellulosic biomass is also used as a feedstock in this process, but its complex structure, due to the cellulose, hemicellulose, and lignin, makes it resistant, thus difficult to use directly in the process. It is therefore advisable to subject this type of biomass to some form of pre-treatment, such as a physical-chemical conversion so that it can be processed using anaerobic digestion (Casau et al., 2022; Sawatdeenarunat et al., 2015). **Fermentation** is mainly used to produce bioethanol. Yeasts or bacteria are used to convert the sugars that exist in the biomass into biofuels. This process also takes place in an oxygen-free environment. The preferred feedstock for this process is agricultural biomass, such as sugar cane or maize, due to their high sugar content (Casau et al., 2022; Sun and Cheng, 2002).

2.3. Challenges to agroforestry biomass valorization

Agroforestry biomass has gained popularity in recent years, but it still faces challenges in its valorization. While it is considered a sustainable alternative to fossil fuels, there are environmental risks associated with its use, mainly with its intensification, such as soil degradation and loss of biodiversity (Casau et al., 2022). For decades there has been a traditional assumption that biomass is carbon neutral. This assumption was that, if used under sustainable conditions, the carbon dioxide emitted during the combustion of biomass would be offset by the carbon dioxide absorbed during the process of plant renewal. A recent study by Gilbert Ahamer discredits this theory (Ahamer, 2022). The author concludes that only half of the carbon

Table 1
Summary of the different types of pyrolysis processes and their operating parameters. Retrieved from (Jouhara et al., 2018).

Process	Reaction temperature (°C)	Heating rate (°C/min)	Residence time	Feedstock size	Bio-oil yield (%)	Bio-char yield (%)	Gas yield (%)
Slow pyrolysis	300–550	50	5–30 min	Whole	20–50	25–35	20–50
Intermediate pyrolysis	300–450	200	25–35h	Coarse	35–50	25–40	20–30
Fast pyrolysis	3000–1000	10–1000	2s	Finely ground	60–75	10.25	10–30

emitted is absorbed by growing plants. To this carbon balance must be added the secondary emissions associated with harvesting, transport, and conversion. In this way, the biomass value chain is not carbon neutral, which is an environmental challenge.

Technologically, several challenges are identified in the literature, mainly related to availability and seasonality of biomass (Mafakheri and Nasiri, 2014). Seasonality directly affects the availability of biomass and the potential scarcity of resources, thus affecting the resilience of supply chains (Mafakheri and Nasiri, 2014). Inefficiency of some conversion processes and lower quality energy products from biomass valorization are also concerns.

From a social point of view, investment in renewable energy is associated with the creation of new jobs along the supply chain, regional development, and self-sufficiency in energy production (Krajnc and Domac, 2007; Mafakheri and Nasiri, 2014; Thornley et al., 2008). However, these benefits are often not understood at the local level, leading to negative impacts on public perception. For example, the construction of power plants is, sometimes, only seen as a threat by local people, who do not accept these plants despite the benefits they bring to the community (Mafakheri and Nasiri, 2014).

Politically and legally, there is a major conflict of interest between biomass producers, sellers, and buyers of biomass (Singhvi and Gokhale, 2019). The literature also mentions the lack of standards and support for the development of sustainable supply chains. Logistical challenges are particularly relevant in residual biomass valorization, as developing robust and sustainable supply chains is difficult and high logistics costs are identified (Goldemberg, 2009; Singhvi and Gokhale, 2019). Techniques for analyzing the location of infrastructure involved in the supply chain are essential for the residual biomass recovery market. Finally, there are also economic challenges, that include the investment and maintenance costs required to develop biomass valorization facilities (Mafakheri and Nasiri, 2014). Another challenge is the variability of biomass supply and demand which results in the variation of biomass prices (Singhvi and Gokhale, 2019).

2.4. *Rural fires*

An important role must be acknowledged for the concern and awareness about forests and rural fires within society. It is recognized that forests are vital for planet Earth, playing a key role in biodiversity conservation and offering a range of products and services, including carbon storage and resources. The environmental, economic, and social impacts of rural fires are also significant and warrant attention (Attri et al., 2020). These impacts include loss of raw materials and biodiversity, contributing significantly to massive carbon dioxide emissions, and effects on soil depletion, where structure, texture, porosity, and water holding capacity are affected (Attri et al., 2020; Halba et al., 2022; Rodrigues et al., 2023a).

Rural fires can easily happen and are often caused by human behavior or natural causes like lightning or very high temperatures. Factors such as climate, land type, and the presence of fuel influence the rural fires (Nunes, 2012). Dry forest residues left in forests are one of the main causes of forest fires, since they act as fuel to the fires (Halba et al., 2022). According to Moreira et al., three aspects should be considered in rural fire prevention: a) facilitating access to the forest; b) dividing the forest into small units to limit the spread of fires more easily; and c) removing forest fuels to reduce the severity of fires (Moreira et al., 2010). Rural fires are one of the most damaging phenomena for the environment and forests in the Mediterranean region today (Fernandes et al., 2016; Ferreira et al., 2015; Nunes et al., 2021c, 2022; Oliveira et al., 2023).

It is estimated that forest fires affect more than 350 million hectares worldwide every year (Attri et al., 2020). In Portugal alone, in 2022 occurred 10449 rural fires, corresponding to a burnt area of 110,007 ha. This is the 4th lowest number of fires and the 5th highest number of burnt area since 2012 (ICNF, 2022). In Portugal, the most common causes of fires, in 2022, were Incendiarism - attributable (28 %) and forest or agricultural burning (19%). The different types of burning account for 41% of the total number of causes, surpassing Incendiarism – attributable. These figures show that both forest management and the recovery of agroforest waste are essential to reducing fires. Assuming that the removal of forest residues contributes to a reduction in the risk of fire, it is assumed that the valorization of the biomass, in this case agroforestry will contribute to a reduction in the number of fires and their severity. There are a few studies that demonstrate this relationship between the valorization of residual forest biomass and the reduction in the number of fires. A Study carried out in (Regos et al., 2016) evaluates how the removal of forest biomass can reduce the number of fires and the area of forest burnt, using a simulation approach. The authors concluded that the removal of biomass for energy purposes can reduce the number of fires and, consequently, the area of forest burnt, especially in the case of large fires. Also in (Halba et al., 2022), the authors state that the gasification of forest biomass has several advantages including a reduction in the number of fires.

As stated by Pivello et al., it is imperative to properly classify rural fires, considering causes related to climate change or inappropriate management practices by farmers (Pivello et al., 2021). This classification is crucial for understanding how such fires may affect the availability of biomass and the development of biofuels (Nunes et al., 2021b). Climate changes, resulting in drier conditions and higher temperatures, can increase the frequency and intensity of fires, thereby reducing the amount of biomass available for energy use (Jones et al., 2022). On the other hand, improper agricultural management practices, such as the uncontrolled burning of agricultural residues, also significantly contribute to the increased risk of rural fires (Souza et al., 2023). These factors together not only exacerbate the loss of biomass but also negatively influence the potential for regional bioenergy development. Therefore, a clear understanding of the causes of rural fires is essential for formulating effective strategies aimed at sustainable biomass management and the promotion of bioenergy development (Pinto et al., 2022).

2.5. *Roadmap*

Roadmaps have emerged as support tools for strategic planning and are used in several domains. such as product development, technology, industry, government, and academia and can have different objectives (Amer and Daim, 2010; Kappel, 2001). In the late 1970s, Motorola started using a roadmap to guide their product development, in a formal way. While Motorola was the pioneer in formally adopting this roadmap approach, there are indications that others might have used a similar method even earlier, possibly in the early 20th century. There are various definitions of roadmap and roadmapping (Amer and Daim, 2010; Galvin, 1998). Roadmapping is the process of developing a roadmap. In the realm of technology, conventional technology roadmaps are visual tools that illustrate and convey connections between markets, products, technologies, and resources over time. These roadmaps help predict the future direction of technological development and assist in decision-making (Amer and Daim, 2010; Matani et al., 2019). Scientific roadmaps started to be used in scientific research in the late 1990s, as they started to be seen as helpers in boosting scientific credibility and accelerator of knowledge production (Galvin, 1998).

Roadmaps have usually a two-dimensional structure, with the horizontal axis representing time in the short, medium, and long term. The vertical axis contains various inputs that can include: market, product, technology, research and development, and resources (Garza Ramos et al., 2022). Three questions aim to be answered by roadmaps (Amer and Daim, 2010) (See Table 2).

Roadmaps are actual documents that take inspiration from the past to predict the future, systematizing all the information in a graphic form that is easy to interpret (Barker and Smith, 1995; Willyard and McClees, 1987). Despite existing different ways of presenting roadmaps, the most common approach was proposed by the European Industrial Research Management Association (EIRMA) (Technology roadmapping, 1997). In this proposal, the roadmap presents a graphic structure, which includes the time component and several layers that include commercial and technological aspects. This structure makes it possible to identify the relationships between the development of markets, products, and technologies to be exploited. Fig. 1 illustrates this structure.

There are, in the literature, several methods and approaches for developing technology roadmaps (Amer and Daim, 2010; Garcia and Bray, 1997; Martin and Daim, 2012; Phaal et al., 2001). It is recommended to use appropriate roadmap structure and developing method depending on the overall goal of the roadmap (Amer and Daim, 2010). A study by Garcia and Bray (1997) presents a roadmap development process that is divided into three phases: 1) preliminary activities; 2) roadmap development; 3) follow-up activities. In the first phase, the scope in which the roadmap will be developed is defined and it is ensured that various conditions can be met so that the roadmapping process can be carried out. In the second phase, various steps are taken to enable the roadmap to be developed, including the identification of barriers and drivers to the technology, as well as the drafting of documents relating to the roadmap. In the third and final phase, the roadmap is validated by experts, a roadmap implementation plan is drawn up and this phase also includes reviewing and updating the roadmap over time, when necessary. In (Martin and Daim, 2012), the authors propose a structure in which three groups of experts are used. The first group is responsible for identifying emerging technologies, the second group identifies market and business drivers, and the last group is responsible for drawing the roadmap and identifying potential gaps. Another methodology to support the development of roadmaps is the T-plan methodology, which was developed by the University of Cambridge and turned into a guide to support the development of roadmaps in companies. In this methodology, the roadmapping process is divided into four workshops. The first three workshops focus on the market, product, and technology layers. In the last workshop, the roadmap is drawn (Phaal et al., 2001). It is quite common to find articles in the literature that combine the roadmapping process with other strategic planning tools, such as SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), PEST analysis (political, economic, social, and technological), the DELPHI method, among others (Amer and Daim, 2010; Brenden et al., 2009; Ho and O'Sullivan, 2017; Lee et al., 2009). These tools help in the roadmapping process, as they make it possible to assess the technological landscape and the market situation (Amer and Daim, 2010). The roadmapping process can bring numerous benefits to organizations, such as making decision-making regarding technological investment easier, serving as marketing tools, bringing experts together, and making it easier to interpret and summarize the main aspects of the topic (Barker and Smith, 1995; Garcia and Bray, 1997; Kostoff and Schaller, 2001). However, there are challenges in the roadmapping process, such as the lack of detailed guidelines, the need for constant adaptation to each situation, and the need to keep the roadmap updated as new technologies emerge daily and circumstances change over time (Brown and O'Hare, 2001; Fernandes et al., 2023a; Lee and Park, 2005).

Table 2
Questions roadmaps aim to answer.

	Where are we now?	Where are we going?	How do we get there?
Objectives	Present the state of the art of the technology, product, and market.	Present the project or technology's vision, mission, and goals.	Develop policies, action plans, and R&D initiatives.

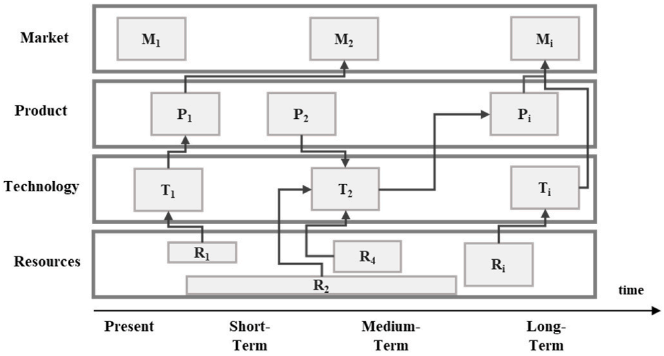

Fig. 1. Roadmap's structure proposed by EIRMA. Adapted from (Technology roadmapping, 1997).

2.6. *Integrating multi-criteria decision methods with roadmapping*

Few articles have been found in the literature that integrate the roadmapping process with any MCDM method, at least from the perspective of a structured roadmap. Lee et al. (2011) use a fuzzy analytic hierarchy process (AHP) to prioritize different technologies in the hydrogen production. The identification of these technologies was presented in another article by the same authors, where they proposed a roadmap for energy in South Korea (Lee et al., 2009). In this article, 5 alternative technologies are evaluated based on 4 criteria - economic impact, commercial potential, internal capacity, and technical spin-off, through feedback gathered from 8 experts. In (Matani et al., 2019) the authors develop a roadmap for sustainable green hydrogen production, combining the T-plan roadmapping technique with a new fuzzy multi-aspect multi-criteria decision-making (F-MaMcDm) approach. The F-MaMcDm was used to prioritize hydrogen production techniques, identifying the most emerging and placing them on the short-term of the roadmap. In this study, the roadmap developed had 4 layers: Technological, Sociopolitical, Environmental, and Economic. The authors state that the use of F-MaMcDm helps experts develop a technological roadmap with dynamic and flexible characteristics, allowing organizations to re-evaluate and adjust the roadmap according to potential changes. Also in (Jeon et al., 2011), a structured roadmap is constructed, combining the AHP (Analytic Hierarchy Process) method to incorporate a supplier selection layer into a roadmap in the semiconductor industry. Ghazinoory et al. (2014) propose a fuzzy-PROMETHEE method for the integration of decisions in the roadmapping process. The alternatives used in this study are nine types of wind turbines which are compared using two groups of criteria: six criteria related to the capacity of the turbines and eight related to their attractiveness. Although this article proposes this method, it does not ultimately present the construction of the roadmap for the situation in question. It should be emphasized that most of the articles found in the literature are in some way related to the energy sector and most of them apply an MCDM method to obtain a ranking of a certain type of technology related to this sector. Regarding the use of the PROMETHEE method, no article was found in the literature combining roadmapping with this method. Bearing in mind that

PROMETHEE has grown to be one of the most widely used and most efficient of the existing methods, there is relevance in combining this method with the roadmapping technique (Singh et al., 2021). This creates a gap in the scientific literature to which this work aims to respond.

3. PROMETHEE II- roadmap (P2RM)

This section will propose a model for developing roadmaps that integrates the multi-criteria decision-making (MCDM) method PROMETHEE II with the roadmapping process. It is the first time that this MCDM method has been combined with the roadmapping process. PROMETHEE has grown to be one of the most widely used and most efficient of the existing methods, there is relevance in combining this method with the roadmapping technique (Singh et al., 2021).

3.1. *Multicriteria problems*

Multicriteria decision problems can be of two types (Brans and Mareschal, 2005):

$$\max\left\{g_1(a), g_2(a), \ldots, g_j(a), \ldots\, g_k(a)\middle| a \in A\right\} \tag{3.1}$$

$$\min\left\{g_1(a), g_2(a), \ldots, g_j(a), \ldots\, g_k(a)\middle| a \in A\right\} \tag{3.2}$$

where A is a finite set of alternatives $\{a_1, a_{2,} \ldots, a_i, \ldots, a_n\}$ and $\{g_1, g_{2,} \ldots, g_i, \ldots, g_n\}$ a set of decision criteria. When applying an MCDM method it is expected to find the alternative that optimizes all the criteria. In most decision problems, not all the criteria can be optimized, as they are antagonistic. Thus, in multi-criteria decision problems, what is often obtained is a compromise solution between the different criteria, since optimizing all the criteria individually is unachievable (Brans and Mareschal, 2005).

The basic information of a multi-criteria decision problem consists of an evaluation table, like the one in Table 3. Each cell in the table shows the scores associated with each alternative per criterion.

Decision problems are usually multi-criteria, and there are no absolute solutions since the solution depends on the preferences of each decision-maker. To represent the decision-maker's preferences, the following relationships are defined (Brans and Mareschal, 2005):

$$\begin{cases} \forall j : g_j(a) \geq g_j(b), \\ \exists j : g_k(a) > g_k(b), \end{cases} \Leftrightarrow aPb, \tag{3.3}$$

$$\forall j : g_j(a) = g_j(b) \quad \Leftrightarrow aIb \tag{3.4}$$

$$\begin{cases} \exists s : g_s(a) > g_s(b), \\ \exists r : g_r(a) < g_r(b), \end{cases} \Leftrightarrow aRb, \tag{3.5}$$

$j = 1, \ldots, m;\ k = 1, \ldots, m.$

Where P represents preference, I indifference, and R incomparability.

According to the first branch of equation (3.3), an alternative is better than another if it is better in at least one criterion and at least as good as the other in the remaining criteria. The second branch of equation (3.4) indicates that the alternatives are equal in all criteria and therefore there is indifference between them. The third and final branch (3.5) indicates that if in a criterion *s* an alternative is the best, but in a criterion *r* another solution is the best these solutions are incomparable, at least in absence of additional information. Incomparability exists in most pairwise comparisons, so additional information is required to decide. Several types of additional information can be used (Brans and Mareschal, 2005). The development of MCDM methods has been driven by real-world situations where multiple criteria needed to be considered, as well as decision-makers' desire to leverage recent developments in mathematical optimization techniques, scientific computing, and computer technology in the decision-making process (Alvarez et al., 2021). The three main types of decision problems where MCDM can be used are: ranking problems, sorting problems, and choice problems (Gonçalves et al., 2015).

Table 3
Evaluation table.

a	$g_1(.)$	$g_2(.)$	…	$g_j(.)$	…	$g_k(.)$
a_1	$g_1(a_1)$	$g_2(a_1)$	…	$g_j(a_1)$	…	$g_k(a_1)$
a_2	$g_1(a_2)$	$g_2(a_2)$	…	$g_j(a_2)$	…	$g_k(a_2)$
…	…	…	…	…	…	…
a_i	$g_1(a_i)$	$g_2(a_i)$	…	$g_j(a_i)$	…	$g_k(a_i)$
…	…	…	…	…	…	…
a_n	$g_1(a_n)$	$g_2(a_n)$	…	$g_j(a_i)$	…	$g_k(a_n)$

3.2. *Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)*

Developed by Jean-Pierre Brans in 1982 and further developed by Vincke and Brans in 1985, PROMETHEE is a multi-criteria decision method (Brans and Mareschal, 2005). Though PROMETHEE is possible to obtain the ranking of various alternatives considering a set of criteria. When first presented this method included two variants, PROMETHEE I, used to obtain a partial ranking of alternatives, and PROMETHEE II, used to obtain a total ranking of alternatives (Brans and Mareschal, 2005). Several variants of PROMETHEE have been developed over the years. A summary of all these variants can be found in Table 4.

PROMETHEE II is applied by comparing alternatives pair by pair for each criterion. For each of the alternatives, these criteria must be either maximized or minimized. Two types of additional information is required for the method's implementation (Behzadian et al., 2010; Brans and Mareschal, 2005).

- Information between criteria - To define the relative importance of each criterion, the decision-makers are asked to assign weights to them. The greater the weight assigned, the more important the criterion becomes. It is common to use standardized weights and for simplicity's sake they can be considered:

$$\sum_j^k w_j = 1, \tag{3.6}$$

$j = 1, 2, \ldots, k.$

Table 4
PROMETHEE variations.

Method	Characterization	Ref.
PROMETHEE I	Partial ranking of alternatives	Behzadian et al. (2010)
PROMETHEE II	Total ranking of alternatives	Behzadian et al. (2010)
PROMETHEE III	Ranking based on intervals	Behzadian et al. (2010)
PROMETHEE IV	Partial or total ranking of alternatives for an infinite set of alternatives	da Cunha et al. (2022)
PROMETHEE V	Used for problems with segmentation constraints	(Behzadian et al., 2010; Brans and Mareschal, 1992)
PROMETHEE VI	Helps the decision-maker determine the weights of the different decision criteria	Brans and Mareschal (1995)
PROMTHEE GDSS	Used in group decision-making	Mareschal et al. (1998)
PROMETHEE - GAIA	Graphical analysis to Support the method	da Cunha et al. (2022)
PROMETHEE TRI	Used in sorting problems	Behzadian et al. (2010)
PROMETHEE CLUSTER	Used in problems of classifying alternatives into classes	Behzadian et al. (2010)

Where w_j is the weight of criterion *j*.

- Information within each criterion - The deviation between the evaluations of two alternatives per criterion is considered $(d_j(a,b))$. When there is a small deviation, the decision-maker gives a small preference to the best alternative or even no preference at all if the deviation value is considered negligible. The preference information within the criteria is obtained through a preference function, P_j, which reflects the differences in evaluation between two solutions for a criterion $(P_j(a,b) = F_j[d_j(a,b)] = F_j[g_j(a) - g_j(b)])$. The result of the preference function can be considered a number. In the PROMETHEE method, six preference functions have been defined that can be used, as shown in Fig. 2 (Brans and Mareschal, 2005).

The preference between two alternatives is expressed using equation 3.7. $\pi(a, b)$ shows the degree of preference of alternative *a* over *b* and $\pi(b, a)$ the degree of preference of alternative *b* to *a* (Silva et al., 2017).

$$\begin{cases} \pi(a,b) = \sum_{j=1}^{k} P_j(a,b)w_{j,} \\ \pi(b,a) = \sum_{j=1}^{k} P_j(b,a)w_{j,} \end{cases} \tag{3.7}$$

Typically, $\pi(a, b)$ and $\pi(b, a)$ are both positive since there are criteria where *a* is preferable to *b* and others where *b* is preferable to *a*. It is evident that if $\pi(a, b) \sim 0$ there is a weak global preference of *a* over *b*, and if $\pi(a, b) \sim 1$ there is a strong global preference of *a* over *b*.

3.3. Outranking flows

Each of the *n* alternatives faces competition from the remaining (*n* - 1) alternatives. To compare the alternatives, outranking flows must be defined. The superiority of an alternative to the remaining is expressed through the positive outranking flow $(\varphi^+(a))$. The higher its value, the better the alternative. On the other hand, the negative outranking flow $(\varphi^-(a))$ expresses how the alternative *a* is surpassed by the others, the lower this value, the better it is the alternative (Alvarez et al., 2021; Kazimieras Zavadskas et al., 2019).

- **Positive outranking flow:**

$$\varphi^+(a) = \frac{1}{n-1}\sum_{x\epsilon A}\pi(a,x), \tag{3.8}$$

- **Negative outranking flow:**

$$\varphi^-(a) = \frac{1}{n-1}\sum_{x\epsilon A}\pi(x,a), \tag{3.9}$$

3.4. PROMETHEE II

PROMETHEE II allows decision-makers to obtain a complete ranking of a finite set of alternatives (Behzadian et al., 2010). Besides the previously mentioned steps, the method must be completed by calculating the net outranking flow $(\varphi(a))$. This is done, by subtracting the negative outranking flow $(\varphi^-(a))$ from the positive outranking flow $(\varphi^+(a))$.

3.5. PROMETHEE group decisions support system (GDSS)

PROMETHEE GDSS is one of the variants of the PROMETHEE method. This variant is used in group decision-making. In the original proposal for this variant, the authors divide the methodology into 3 phases (Mareschal et al., 1998).

- Preliminary Phase - In this phase, the decision problem is structured.
- Individual assessment - In this phase, the opinion of each of the decision-makers is assessed, considering the PROMETHEE methodology.
- Overall assessment - The overall assessment stage involves combining the opinions of all decision-makers to reach the best decision by consensus. This is achieved by calculating the average of individual net outranking flows $(\varphi(a))$ using the PROMETHEE II

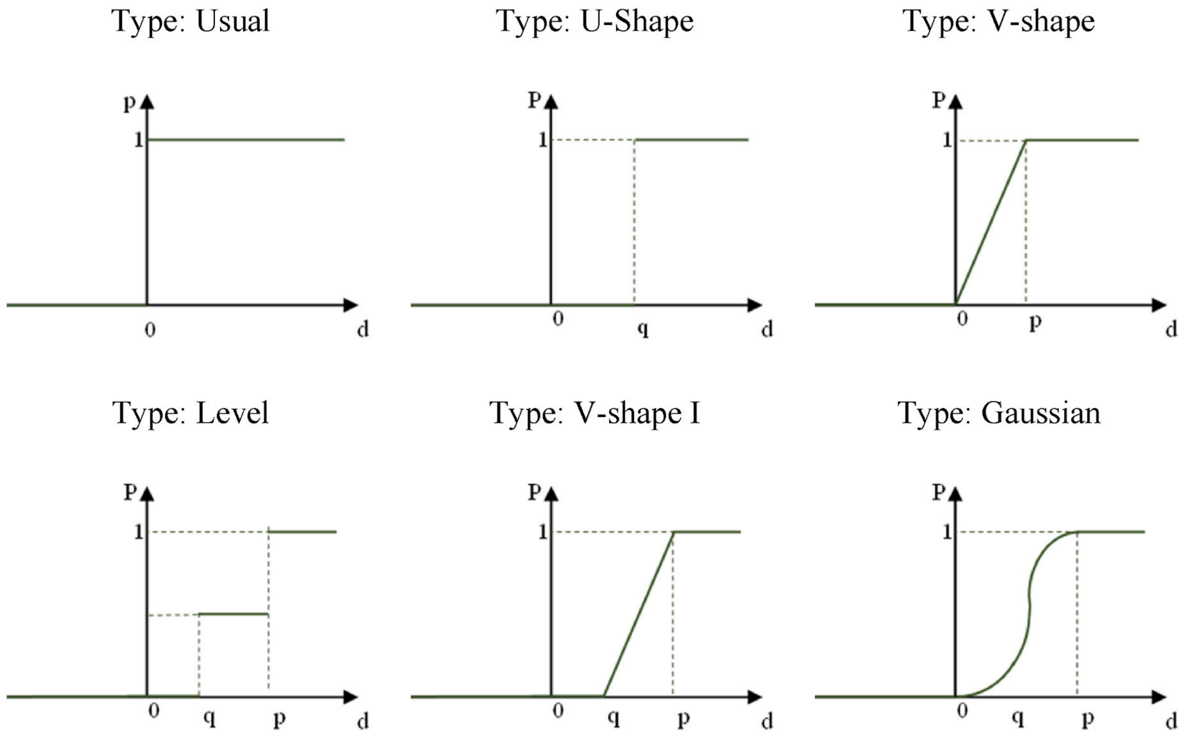

Fig. 2. Preference functions.

method, which can be arithmetic or weighted based on the weights of decision-makers.

3.6. Proposal of an integrated PROMETHEE II-roadmap model (P2RM)

This paper proposes a model for developing roadmaps, integrating the MCMD PROMETHEE method into the roadmapping process. This integration gives the roadmapping process more dynamic and flexible characteristics (Matani et al., 2019). These characteristics are essential when it comes to technological issues, which are constantly changing. The P2RM model proposed for building roadmaps is divided into seven steps, that will be explained below. Fig. 3 summarizes the model.

3.6.1. Characterization and theoretical foundation of the topic and roadmap planning

The proposed model begins by characterizing the topic of roadmap, since in-depth knowledge of the topic in question is essential when developing any roadmap. Thus, in this step, which is part of the roadmap planning phase, the scope and objectives of the roadmap must first be defined, as well as the structure of the roadmap to be used, deciding which layers are most appropriate taking into account the topic in question (Lee et al., 2011; Singh et al., 2021). It also outlines the time horizon for the roadmap's construction. This step should include an initial characterization of the current state of the technology, product, or market for which the roadmap is being developed. This characterization must be as detailed as possible, as the future state of a technology is directly influenced by the current state. In this characterization phase, some complementary tools can be used to support this process, such as SWOT analysis and/or PEST (political, economic, social, and technological) analysis (Amer and Daim, 2010). Also at this stage, those responsible for developing the roadmap should characterize the future state of the technology using existing literature and/or non-scientific documents. This characterization should identify, when possible, potential future scenarios, opportunities, and threats to the technology under analysis.

3.6.2. Decision's problem definition

Defining a decision problem requires three main components (Saaty, 1994). In this second phase, these three components must be clearly defined. At this stage, existing literature should be used, as well as the opinion of experts in the field, when possible.

- General objective of the decision problem - The main objective to which the decision model used must help provide an answer must be identified, as well as the question asked to achieve the desired answer. The decision problem's objective is directly related to the scope and objectives of the roadmap.
- Definition of decision criteria - A thoughtful and assertive choice of the decision criteria must be made. These criteria can be defined with

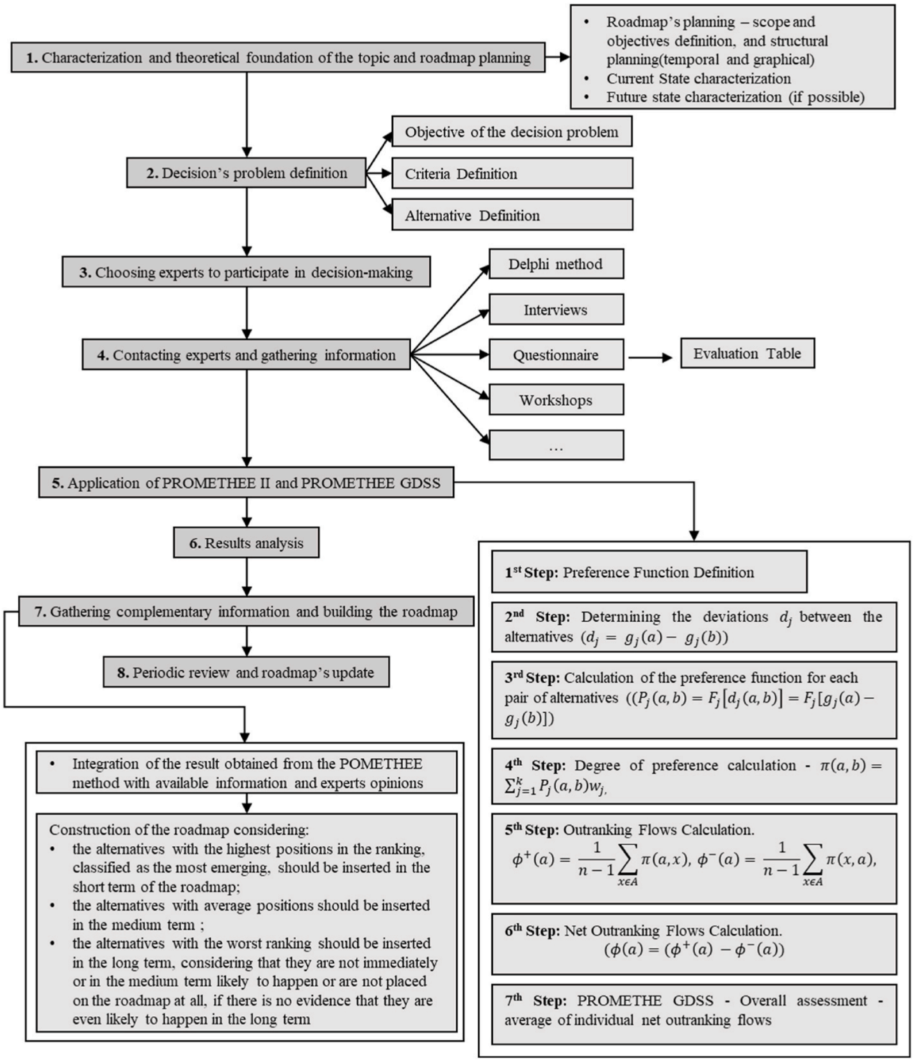

Fig. 3. P2RM model proposed.

the help of experts in the area in which the roadmap is being developed and by considering the existing literature.

- Defining alternatives - Simultaneously, the alternatives that answer the decision problem must be defined. In this step, experts can also be consulted, as well as the existing literature.

3.6.3. *Choosing experts to participate in decision-making*

In the third step of the proposed model, the decision-makers who will take part in the decision are chosen. These decision-makers must be experts in the roadmap's topic. These experts can be found in numerous ways, through social networks such as LinkedIn and ResearchGate; through research articles; organizations, among others. The group of experts must be heterogeneous, multidisciplinary, and technically diverse (IEA - International Energy Agency, 2014; Martin and Daim, 2012).

3.6.4. *Contacting experts and gathering information*

Gathering information from the experts that will feed into the roadmap is a critical stage in the process that requires some prior planning. In this planning phase, it must be decided how best to collect information from experts. There are numerous methods listed in the literature that have been used to develop roadmaps. The choice of which method to use must be adapted to each situation and must consider aspects such as the time and resources available to carry out the roadmap and whether it is applied to a small or large environment. One of the most traditional methods for gathering information is the Delphi method, which is a qualitative forecasting method. This method has already been used in the roadmap development process (Martin and Daim, 2012). This method is not applicable in some situations, as it can become a time-consuming process with high implementation costs (Lahoti et al., 2018). Another way of obtaining information that can be applied is structured or semi-structured interviews with experts or workshops. Another form of information gathering used in roadmapping techniques is questionnaires (da Cunha et al., 2022; Fernandes et al., 2023b; Matani et al., 2019). There is great freedom to choose the best way of obtaining information, which must be adapted to each situation. Once the best way to obtain information has been chosen, the selected experts should be contacted, and the necessary information should be collected. Once the respondents have been contacted, an evaluation table like the one in Table 3 should be obtained for all of them.

3.6.5. *Application of PROMETHEE II and PROMETHEE GDSS*

Once all the necessary information has been collected the PROMETHEE II method should be applied. Appropriate software should be used. The net outranking flows $(\varphi(a))$, per decision-maker and alternative, and, consequently, the ranking of the alternatives for all decision-makers should be obtained. Finally, the global ranking of the alternatives must be obtained through phase 3 of PROMETHEE GDSS, where the arithmetic or weighted average of the net outranking flows $(\varphi(a))$ is calculated.

3.6.6. *Results analysis*

With the individual and global rankings obtained, these must be analyzed carefully and with some sensitivity, to understand whether the results obtained make sense. This analysis should consider what is reported in the literature, to understand whether the results are consistent with the available information.

3.6.7. *Gathering complementary information and building the roadmap*

The roadmap to be built must be fed by the results obtained from the application of PROMETHEE II and PROMETHEE GDSS and by available information in documents related to the topic and information obtained from experts, who can be people that have taken part in the previous decision-making process or not. The integration of different sources of information makes it possible to fill in gaps, strengthen and complement the information obtained (Fernandes et al., 2023b). In addition to the current state, the roadmap has three associated periods: the short, the medium and the long term. The ranking obtained through PROMETHEE is integrated with the roadmap by placing the alternatives with the highest positions in the ranking, classified as the most emerging, in the short term of the roadmap; the alternatives with average positions in the medium term and the alternatives with the worst ranking in the long term, considering that they are not immediately or in the medium term likely to happen or are not placed on the roadmap at all, if there is no evidence that they are even likely to happen in the long term. The feeding of the roadmap from the ranking obtained should be done in close connection with existing literature and documents, and if necessary supplemented again with the opinion of one or more experts. The PROMETHEE method may not be used to build all the layers of the roadmap directly.

3.6.8. *Periodic review and roadmap's update*

One of the most important aspects to consider when talking about roadmaps is the fact that they are a "living process" that continues and changes beyond the date of publication. Roadmaps therefore need to be revised and adapted to potential changes in circumstances. There is no certain period at the end of which the roadmaps should be kept up to date, but the authors must be aware of any changes that may occur that could alter the course defined by the roadmap (IEA - International Energy Agency, 2014).

4. Application of the P2RM model to the valorization of RAFB

In this section, the proposed P2RM model will be applied to the specific case of the valorization of RAFB in Portugal.

4.1. *Characterization and theoretical basis of the topic and roadmap planning*

The roadmap is being built within the scope of the valorization of RAFB in Portugal and aims firstly to characterize the current state of this market in Portugal and demonstrate its future trends. The roadmap follows the structure proposed by EIRMA. This structure consists of 4 layers - Market, Products, Technology, and Resources (Technology roadmapping, 1997). For the roadmap's time horizon 7 years were considered, starting from 2023 to 2030. Three-year intervals are taken into consideration while defining the short, medium, and long terms in the roadmap. This structure and time definition has already been used in other roadmap proposals (Arcos-Novillo and Güemes-Castorena, 2017; Fernandes et al., 2023b).

4.2. *Decision's problem definition*

4.2.1. *General objective of the decision problem*

The application of PROMETHEE will be made to determine the most favorable and emerging conversion technologies of biomass valorization, in the context of Portugal, and the results will feed the technological layer of the roadmap. It is therefore necessary to define decision criteria and alternatives. This is a maximization problem, in all the criteria since the aim is to choose the alternatives with the highest scores for all the criteria.

4.2.2. *Definition of criteria*

Through a literature review, it was possible to identify the most relevant criteria for this study. The four criteria used are Environmental, Sociopolitical, Technological, and Economic. It should be emphasized that the criteria include the 3 pillars of sustainability, allowing for economic, social, and environmental analysis when making decisions.

4.2.3. *Definition of alternatives*

The alternatives correspond to agroforestry biomass conversion technologies. These alternatives were obtained through a literature review and validated by an expert. The alternatives are listed in Table 5. These technologies are already established as conversion techniques for biomass. (Okolie et al., 2022) performed a comprehensive review on this technologies' technology readiness level (TRL) and concluded that most biological processes have a TRL value of 4–5 and in contrast thermochemical processes are expected to reach a TRL of 9 in the next two decades through detailed research and development, especially the gasification process.

With the criteria and alternatives defined, it is possible to construct the diagram in Fig. 4, which represents the decision problem in question.

4.3. Choosing experts to participate in decision-making

For the study, it is essential to obtain information from two main groups: workers in organizations in the field of RAFB valorization and researchers in the same field in the Portuguese context. These experts were tracked through the social networks LinkedIn, ResearchGate, and Ciencia Vitae.

4.4. Contacting experts and collecting information

To obtain the information from experts, a questionnaire is developed and validated by an expert in the field. The questionnaire is divided into three main parts: characterization of respondents, evaluation of alternatives against criteria, and characterization of the current and future state of RAFB valorization. Decision-makers are presented with alternatives and criteria and are asked to assign weights to the four criteria to identify the most relevant ones. After this, the decision-makers score each alternative against each criterion using a 5-point Likert scale. Since the information is obtained through a questionnaire, it is not possible to directly obtain the preference function that each decision-maker would choose. Therefore, the type II – U-shape preference function is used for all criteria and decision-makers, as this function is the most suitable for cases in which decision criteria with a qualitative scale are used, as is the case (Miller and Mattes, 2014). In this type of function, it is necessary to determine a preference threshold - *p*. This threshold represents the smallest difference that is considered sufficient to generate a total preference on the part of the decision-maker (Brans and Mareschal, 2005). The preference threshold, *p*, is determined by asking decision-makers whether they consider a difference of 1 in the score negligible. Those who answered "no" are given a *p* value of 0.99, while those who answered "yes" are given a value of 1.99. An evaluation table should be obtained for each decision-maker, providing information on the weight given to each criterion and the score for each alternative per criterion. At this stage, the responses of 22 decision-makers (DM's) were considered. The information regarding the DM's experience and areas of work is displayed in Table 6. The DM's scores per alternative and the criteria weights are in Table 7. In this table is possible to see that, for example, DM3 assigned a weight of 10 to the Technological criteria and punctuated, in this criterion, the alternative A2 – Torrefaction with a 3 in the 5-point Likert scale.

Table 5
List of alternatives.

Conversion Type	Alternative (A_i)	Technology	TRL	Ref.
Thermochemical	A_1	Combustion	9	Dovichi Filho et al. (2021)
	A_2	Torrefaction	7–8	Kappler et al. (2022)
	A_3	Pyrolysis	7–8	Shen et al. (2020)
	A_4	Direct Liquefaction	2–5	Shahbeik et al. (2024)
	A_5	Gasification	7–8	Bauen et al. (2020)
Biologic	A_6	Anaerobic Digestion	4–5	Okolie et al. (2022)
	A_7	Fermentation	4–5	Okolie et al. (2022)

4.5. Application of PROMETHEE II and PROMETHEE GDSS

The PROMETHEE II decision model is applied using the Visual PROMETHEE Academic Edition software (VP Solutions, 2013). With the information gathered from the DM's, the model was implemented in the mentioned software. In the software is possible to obtain the ranking of the alternatives for each decision-maker and the overall ranking of all the decision-makers, using PROMETHEE GDSS. To obtain the overall ranking an arithmetic means of the decision-makers' individual outranking flows ($\varphi(a)$) is calculated.

4.5.1. PROMETHEE II and PROMETHEE GDSS results

The DM's evaluated four decision criteria based on their importance to the problem. The average weights for the 22 decision-makers were 27% for the "Technological" criterion, 22% for the "Sociopolitical" criterion, 24% for the "Environmental" criterion, and 27% for the "Economic" criterion. The "Sociopolitical" criterion was considered the least important, with 12 decision-makers considering it the least important. The "Technological" and "Economic" criteria had the same average value, but only 4 decision-makers scored the "Technological" criterion the highest. The "Environmental" criterion was considered the most relevant by one decision-maker and the least relevant by three. Fig. 5 shows the individual ranking of all the decision-makers, as well as the overall ranking. The "Direct Liquefaction" alternative appears at the bottom of the ranking in eight DM's and only in the DM16 and DM21 rankings does this alternative appear in first place. These scores show that the "Direct Liquefaction" alternative is not a viable option in the short or medium term for the valorization of RAFB in Portugal. Fermentation was another low-scoring alternative, appearing in the last position for five DM's and in the first position for three. "Anaerobic Digestion" and "Gasification" are the alternatives that appear at the top of the rankings most often. On the other hand, the "Anaerobic Digestion" alternative is the worst ranked by five decision-makers while in only one of the rankings, the "Gasification" alternative comes last. This shows that although the "Anaerobic Digestion" alternative appears more often at the top of the rankings, the "Gasification" alternative is more consensual among decision-makers. The next alternative with the most positions at the top of the rankings is the "Pyrolysis" alternative. This alternative is ranked first by five decision-makers and last by only one. The "Torrefaction" alternative also scored well individually, coming first in six rankings and last in four, Finally, the "Combustion" alternative occupies first place in three of the rankings and last place the same number of times.

Table 8 contains the net outranking flows per DM and alternative and Table 9 shows the global ranking obtained using the PROMETHEE GDSS method, as well as the respective global net outranking flows ($\varphi^G(a)$), which is the average of the net outranking flows per DM and alternative. The higher the values of the net outranking flow ($\varphi(a)$) the better the performance of the alternative. For example, for DM5 the alternative with best performance is Combustion, with a net outranking flow of 0,505. The alternative with the best evaluation is "Gasification". This alternative outperformed the others most times and did so in the most important criteria and was outperformed the fewest times by the others. In second and third place are the alternatives "Torrefaction" and "Pyrolysis". These alternatives have positive $\varphi(a)$ values, meaning that the value of $\varphi^+(a)$ is higher than the value of $\varphi^-(a)$, which means these alternatives were not surpassed by the others. In fourth and fifth place, respectively, there are the "Combustion" and "Anaerobic Digestion" alternatives. Although these alternatives have positive outranking flows, their values are very close to 0, which means that the positive and negative outranking flows have identical values, indicating that these alternatives outperform the others in the same number of criteria as those in which they are outperformed. In the last two positions of the

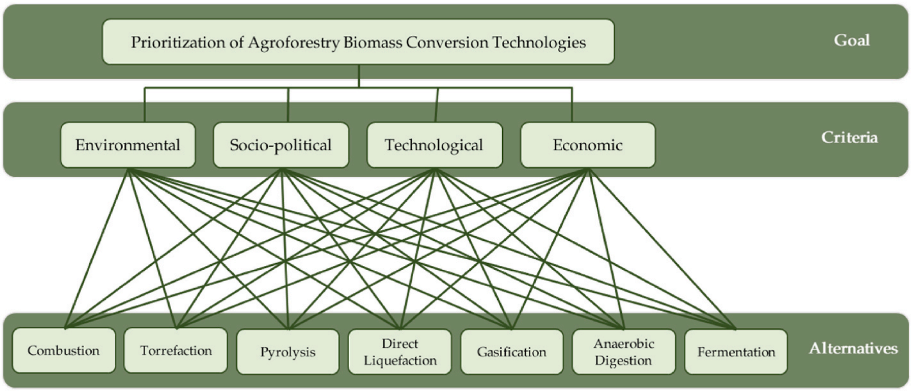

Fig. 4. Decision's problem representation.

Table 6
DM characterization.

DM's	Role	RAFB linkage	Experience (years)
DM1	Professor and researcher	R&D	5–10
DM2	Professor and researcher	R&D	>15
DM3	Professor and researcher	R&D	10–15
DM4	Vice-president for the Biomass and Energy Center in Portugal	R&D	>15
DM5	Professor and researcher	R&D	10–15
DM6	Administrator	Preparation and supply of biomass	>15
DM7	Researcher	R&D	>15
DM8	Biomass suply chain manager	Management of biomass supply	5–10
DM9	Technician at the Forestry Technical Office	Strategies for recovery of forest biomass	5–10
DM10	Professor and researcher	R&D	>15
DM11	Project manager	Biomass organization	10–15
DM12	Bioenergy technician	Valorization of lignocellulosic residues	5–10
DM13	PhD student	R&D	<5
DM14	PhD student	R&D	<5
DM15	Deputy Director	Pellets production	10–15
DM16	Researcher	R&D	5–10
DM17	Production manager	Torrefied biomass production	5–10
DM18	Production manager	Pellets production	<5
DM19	Chairman of a Forestry Producers Association	Representative of agroforestry biomass producers	>15
DM20	Deputy Director	Construction of a biomass torrefaction unity	<5
DM21	R&D laboratory manager	Biomass pellets for domestic and industrial use	5–10
DM22	Administrator	Biomass company	5–10

ranking, and as expected from the individual analysis of the decision-makers ranking, there are the "Fermentation" and "Direct Liquefaction" alternatives, respectively. The outranking flow values for these alternatives are negative, which indicates that these alternatives are outranked by the others in the most important criteria.

4.6. Gathering complementary information and building the roadmap

Both the current and the future state are characterized using literature and expert opinion. Information was collected from the experts using a questionnaire. This questionnaire contains questions that allow the implementation of the PROMETHEE method, explained in the previous chapter, and questions that are used to collect complementary information that feeds into the different layers of the roadmap. The proposed roadmap for the valorization of RAFB can be found in Fig. 6. The roadmap will be explained in detail, per layer.

4.6.1. Market

In Portugal, the valorization of agroforestry biomass is primarily focused on the energy sector, with the production of electricity and heat and it is expected to continue in the long term. The energy production from residual biomass, mainly through direct combustion, is the principal way in which biomass is valorized, both in industrial and residential terms (Ferreira et al., 2017; Rego et al., 2020). Wood pellets are another major consumer of RAFB, as the pellet market has grown in Portugal and is expected to continue. This production adds value to biomass, increasing energy efficiency and homogenizing it, making it easier to store and transport, combating this way the biggest challenges in biomass recovery (Nunes et al., 2016). It is essential for the viability of biomass to be added to the value chain earlier, with biomass collected and pre-treated locally to reduce storage and transport costs and emissions. This design of value chains should be a priority in the upcoming years (Mottaghi et al., 2022). In this sense the integration of Geographical Information systems (GIS) can be beneficial. GIS can be used to identify optimal locations for prospective biomass infrastructures and to add economic, environmental, and social criteria to the supply chain and can also help in estimation of biomass residues collected (Woo et al., 2018).

Valorization of RAFB is also crucial in forest management, as it directly links the valorization of forest biomass to a reduction in fires. The collection of forestry waste, which is fuel for fires, can be facilitated by agroforestry biomass valorization. Incentives, particularly financial ones, can increase concern among landowners and forest producers to clean up forests and valorize residues. Biofuels are expected to enter the market in the medium term, with the development of certain technologies and existing needs as indicators.

4.6.2. Product

The recovery of agroforestry biomass (RAFB) in Portugal produces electricity and heat, with the agglomerate industry being a major consumer (Rego et al., 2020). The fertilizer and charcoal market also contribute to the products obtained from agroforestry biomass. Portugal's potential for biochar production is evaluated, with the Alentejo region showing potential, given the availability of raw materials in this region, that can be used for its production sustainably (Garcia et al., 2022). In the medium term, syngas production is planned, with the development of gasification techniques. Syngas can be processed into other products like liquid fuels, hydrogen, biomethane, and bioethanol (Rijo et al., 2023). Hydrogen is expected to become a main product from RAFB, as green fuel production is essential (Passos et al., 2020). The Portuguese Recovery and Resilience Plan (PRR) includes several projects aiming to develop green hydrogen and methanol production from

Table 7
Alternative's scores per DM.

DM's	Technological								Socio-political							
	w_t	A_1	A_2	A_3	A_4	A_5	A_6	A_7	w_{sp}	A_1	A_2	A_3	A_4	A_5	A_6	A_7
DM1	10	5	5	4	3	4	5	4	6	4	4	3	2	4	4	3
DM2	10	5	5	5	2	3	1	2	6	2	2	2	2	2	2	2
DM3	10	5	3	3	2	4	4	3	8	5	2	2	2	3	4	2
DM4	5	5	4	3	2	3	4	3	8	3	2	2	2	3	4	3
DM5	9	5	4	3	2	4	1	1	6	2	2	2	2	2	1	1
DM6	10	3	4	5	3	3	3	3	9	3	3	3	3	3	3	3
DM7	8	5	5	5	3	5	5	4	6	2	2	2	2	2	3	2
DM8	7	5	1	3	1	3	4	3	5	3	1	3	3	3	3	2
DM9	3	5	2	4	1	1	2	3	3	2	1	2	1	1	1	4
DM10	10	5	5	5	3	5	5	3	10	3	3	3	3	3	3	3
DM11	9	4	3	4	4	4	3	3	8	4	4	3	3	4	3	3
DM12	10	5	5	4	3	5	5	4	8	3	3	4	3	5	4	3
DM13	10	2	4	4	3	3	3	2	8	2	3	4	4	4	3	3
DM14	10	4	4	4	3	3	4	4	8	3	3	3	3	2	3	3
DM15	8	5	1	1	3	3	2	3	3	3	3	2	2	2	3	2
DM16	9	1	1	4	4	5	5	5	8	1	1	3	4	4	4	4
DM17	10	3	4	5	3	5	3	3	7	3	3	3	3	3	3	3
DM18	7	2	3	3	2	3	2	2	7	2	3	3	2	3	2	2
DM19	7	1	2	2	4	4	3	4	5	3	2	3	2	3	2	3
DM20	9	2	5	5	5	5	5	3	7	3	5	3	5	5	3	3
DM21	8	3	4	3	4	4	3	3	8	3	4	3	4	4	3	3
DM22	8	2	4	2	2	3	1	1	9	2	3	3	2	5	1	3
	Environmental								Economic							
	w_{en}	A_1	A_2	A_3	A_4	A_5	A_6	A_7	w_e	A_1	A_2	A_3	A_4	A_5	A_6	A_7
DM1	8	2	4	2	4	4	4	4	10	5	5	4	2	4	5	3
DM2	10	1	5	5	4	4	3	4	10	4	5	3	1	3	3	1
DM3	5	1	2	2	2	3	3	3	10	5	3	2	2	3	3	3
DM4	6	3	1	2	4	4	4	3	7	4	3	3	3	3	4	3
DM5	10	5	5	5	5	5	1	1	10	5	5	5	5	5	1	1
DM6	10	3	4	4	3	3	3	3	10	3	5	5	3	3	3	3
DM7	6	2	4	4	4	4	3	4	8	5	4	4	3	4	5	3
DM8	7	2	3	3	2	3	3	2	4	5	2	2	2	3	4	3
DM9	7	1	2	1	1	2	3	5	9	2	2	2	2	2	2	2
DM10	10	3	3	3	3	3	3	3	10	3	5	5	2	5	5	3
DM11	8	2	3	4	4	4	2	3	10	4	4	4	3	4	3	3
DM12	10	5	5	5	3	5	5	5	8	5	5	4	4	5	5	5
DM13	9	3	4	4	4	4	4	4	9	3	4	4	4	4	4	4
DM14	10	2	4	3	3	3	5	4	10	4	3	3	2	2	4	4
DM15	5	1	2	4	1	2	2	3	5	4	3	2	3	2	1	1
DM16	9	1	1	4	4	3	4	4	7	3	1	3	3	4	4	4
DM17	8	1	5	5	3	5	3	3	6	4	4	5	3	5	3	3
DM18	7	2	5	3	2	2	2	2	10	2	5	3	2	2	2	2
DM19	6	2	2	2	3	3	3	4	10	3	2	3	3	3	2	4
DM20	7	2	4	3	2	3	5	4	7	5	4	2	2	5	1	2
DM21	9	3	4	3	4	4	3	3	10	3	3	3	4	4	3	3
DM22	9	2	3	2	3	5	5	5	7	4	2	2	3	3	2	3

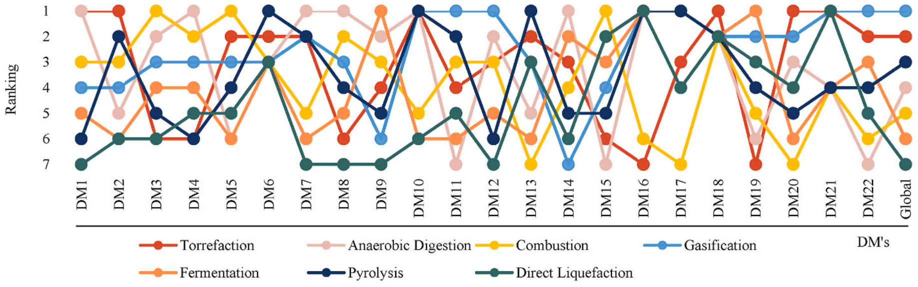

Fig. 5. Individual ranking per DM.

biomass.

4.6.3. *Technology*

This section is mainly fed by the results obtained by the PROMETHEE. The main conversion technology currently used is combustion, either in generation or cogeneration plants or at industrial and residential levels. This use is expected to continue in the long term, as there are several infrastructures built for this purpose. In the ranking obtained using the PROMETHEE method, the "Combustion" alternative came third. This may indicate that although combustion is the main technology for valorizing RAFB today and will continue to be used in the future, there are not many prospects for developing this technology. It

Table 8

Net outranking flow per DM and per alternative.

$(\varphi(a))$	Combustion	Torrefaction	Pyrolysis	Direct Liquefaction	Gasification	Anaerobic Digestion	Fermentation
DM1	0,186	0,461	−0,333	−0,637	0,118	0,461	−0,255
DM2	0,093	0,556	0,278	−0,324	0,046	−0,324	−0,324
DM3	0,697	−0,323	−0,323	−0,525	0,283	0,364	−0,172
DM4	0,256	−0,340	−0,423	−0,244	0,192	0,558	0,000
DM5	0,505	0,376	0,248	0,162	0,376	−0,833	−0,833
DM6	−0,256	0,598	0,684	−0,256	−0,256	−0,256	−0,256
DM7	0,083	0,131	0,131	−0,488	0,131	0,405	−0,393
DM8	0,319	−0,377	0,167	−0,442	0,196	0,515	−0,377
DM9	−0,008	−0,038	−0,053	−0,394	−0,129	0,121	0,500
DM10	−0,083	0,208	0,208	−0,375	0,208	0,208	−0,375
DM11	0,233	0,086	0,310	−0,024	0,576	−0,667	−0,514
DM12	0,148	0,148	−0,167	−0,852	0,482	0,370	−0,130
DM13	−0,204	0,093	0,130	0,037	0,037	0,000	−0,093
DM14	0,035	0,211	−0,009	−0,491	−0,737	0,561	0,430
DM15	0,460	−0,214	−0,095	0,064	−0,016	−0,222	0,024
DM16	−0,621	−0,869	0,298	0,298	0,298	0,298	0,298
DM17	−0,387	0,312	0,602	−0,376	0,602	−0,376	−0,376
DM18	−0,091	0,548	−0,091	−0,091	−0,091	−0,091	−0,091
DM19	−0,244	−0,685	−0,119	0,179	0,387	−0,345	0,827
DM20	−0,417	0,450	−0,133	−0,017	0,411	−0,017	−0,278
DM21	−0,357	0,476	−0,357	0,476	0,476	−0,357	−0,357
DM22	−0,258	0,253	−0,172	−0,182	0,616	−0,328	0,071
GDSS	0,004	0,094	0,035	−0,205	0,191	0,002	−0,122

Table 9

Alternatives' global ranking.

Ranking	a_i	$\varphi^G(a_i)$
1	Gasification	0,1912
2	Torrefaction	0,0937
3	Pyrolysis	0,0354
4	Combustion	0,0041
5	Anaerobic Digestion	0,0020
6	Fermentation	−0,1216
7	Direct Liquefaction	−0,2047

may even happen that, in some situations, this technique will no longer be used to make way for others. The conversion technology first ranked through the PROMETHEE method is the "Gasification" alternative. In the expert's opinion, this is the most emerging technology in the future of residual biomass valorization in Portugal. Currently, this technology is limited to pilot projects, with several reactors scattered around research and development units (Passos et al., 2020). It is hoped that development activities will continue in the short term and that this technology will be commercially available in the medium term. Alentejo is one of the regions with the greatest potential for developing this technology, one of the main reasons being the existing quantities of agricultural, forestry, and agro-industrial waste (Rijo et al., 2023). Gasification is a more environmentally sustainable technology, especially when it comes to greenhouse gas emissions when compared with combustion, and it is considered to be the conversion technology with the greatest sustainable potential in the energy sector (Passos et al., 2020; Rego et al., 2020; Troldborg et al., 2014). For the gasification process to be efficient, it is essential that the biomass has a low percentage of moisture, and so drying processes that precede gasification are necessary (Hamelinck et al., 2004). In the ranking obtained, "Torrefaction" and "Pyrolysis" technologies appear in second and third place respectively. These technologies alone are not the most efficient, but they must be used to pre-process the biomass that will later be used for gasification (Ivanovski et al., 2022). This pre-processing gives the biomass more density, homogenization, and greater energy value (Casau et al., 2022). It is therefore expected that pyrolysis and torrefaction technologies will follow the development of gasification. In fourth place in the ranking is the "Anaerobic Digestion" alternative. This recovery technique is mostly used to produce biogas from non-woody biomass. This recovery technique is promising for agricultural waste and industrial waste from food processing companies, such as nuts, dairy products, cereals, and fruit (Loureiro et al., 2021; Rodrigues et al., 2019). There is still a long way to go in developing this technology, but it is believed to have long-term potential for producing biogas and biomethane. Fermentation techniques and direct liquefaction were occupied in the last positions, showing that these two techniques are not viable in Portugal at the time of the roadmap's development. There is also no information in the literature to indicate that these two techniques will be options for use in Portugal soon.

4.6.4. Resources

4.6.4.1. Raw materials. Agroforestry biomass is divided into two types: lignocellulosic and non-lignocellulosic biomass (Braghiroli and Passarini, 2020). Currently, lignocellulosic biomass, which includes woody biomass, is the most used for recovery and the one with the largest quantity available in Portugal. In the future, with the production of different products such as biogas, more non-lignocellulosic biomass will be used, including some agricultural and industrial waste. This utilization will come about mainly through anaerobic digestion and gasification.

4.6.4.2. Legislation. The Portuguese National Energy and Climate Plan (PNEC, 2030) aims to achieve Portugal's energy and climate objectives for the 2021–2030 period. It emphasizes the decarbonization of the national economy, strengthening renewable energy commitment, and reducing energy dependence. The valorization of biomass is one of the renewable sources that will make it possible to achieve these objectives and is highlighted in this plan as one of the growing renewable sources over the next decade, due to the production of hydrogen and biomethane (Resolução do Conselho de Ministros n.º 53/2020 | DR, n.d.). In Portugal, as part of a policy to valorize renewable energy sources, the plan for the development of biorefineries focuses on biomass valorization, promoting sustainable use of biomass as an energy source, was proposed (Resolução do Conselho de Ministros n.º 163/2017 | DR, n.d.). The plan proposes a national roadmap based on five pillars: promoting raw material supply chains, increasing knowledge and investment in research, development, and innovation, presenting a typology of demonstration projects, technological, social, and environmental monitoring, and involving society and improving demand. The implementation of this plan, which has a 2030 horizon, was supposed to take

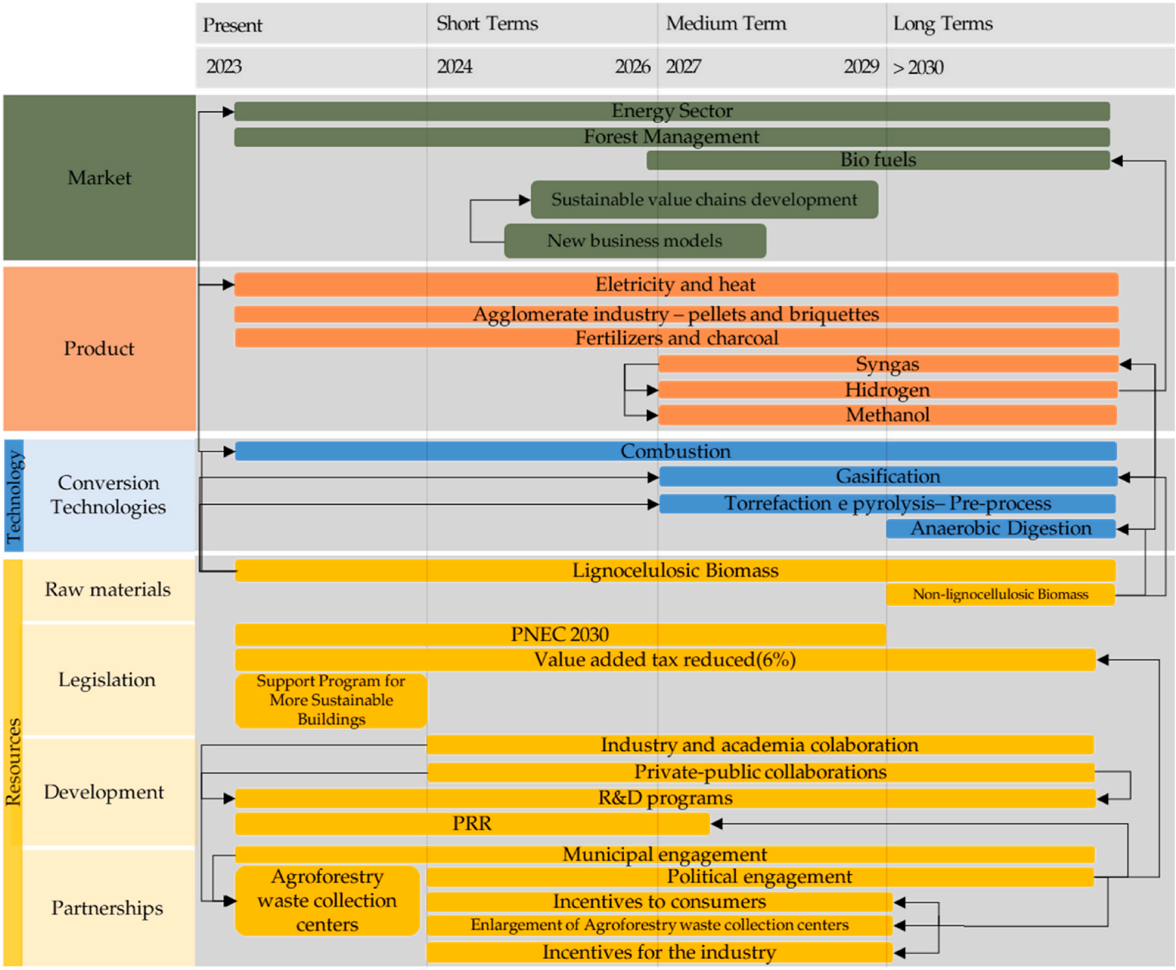

Fig. 6. Proposed roadmap for the recovery of RAFB.

place according to annual action plans, which would be proposed by the "National Platform for Biomass and Biorefineries" - a platform that would be created under the program. However, so far this platform does not appear to have been set up, nor have the annual action plans been published anywhere.

In the 2023 state budget, biomass heating equipment and briquettes and pellets saw a value-added tax reduction from 23% to 6%. The reduction must be maintained in the future. The Support Program for More Sustainable Buildings reimburses consumers for investments in energy efficiency, particularly for biomass boilers and recuperators. These programs are crucial for raising sustainability awareness and promoting changes in daily lives, contributing to carbon neutrality goals, and need to be extended to industry and even to non-residential buildings.

4.6.4.3. Development. Constant investment in the development of this sector is essential for the success of the RAFB valorization market. In this sense, and considering the opinion of the experts, the dissemination of knowledge between all the parties involved is essential. This can be achieved through joint development programs, lectures, and workshops. Knowledge should also be shared along the entire value chain, from producers to end consumers, through local awareness-raising activities. Public awareness of the advantages of using biomass fuels is essential for changing habits. Campaigns to promote the use of biomass fuels are necessary. This can be achieved through joint development programs, lectures, and workshops. Portugal has several R&D projects in biomass valorization, such as Inpactus, Move2LowC, BGW - Bio Green Woods, and Stex (Bio Green Woods, n.d.; PPS4, n.d.; Technologies - Stex Pt, n.d.; Paço et al., 2020). Inpactus aims to create a University-Industry center of excellence, while Move2LowC aims to increase the utilization of different types of biomass for biofuel production. BGW - Bio Green Woods uses forest biomass to produce various products, including methanol, charcoal, briquettes, eucalyptus oils, wood vinegar, and liquid smoke. Despite existing R&D projects in several national units, they should be maintained as they often enable the creation of new knowledge.

4.6.4.4. Partnerships. One of the biggest difficulties in collecting agroforestry waste is small producers or landowners. People who own agroforestry waste often choose to burn it, which is one of the main causes of fires in Portugal (ICNF, 2022). Municipal Facilities are therefore essential at municipal level for disposing of waste (CBE - Centro da Biomassa para Energia, 2021). There are already some municipalities in Portugal that make it easier for residents to collect waste, but this network needs to be extended and greater municipal involvement should exist. A way to help small producers make the most of their waste is to set up centers for the collection and processing of agroforestry waste (Resolução do Conselho de Ministros n.º 53/2020 | DR, n.d.). For example, in the municipality of Penacova, there are already nine agroforestry waste collection centers (Regulamento n.º 973/2020 | DR, n.d.). These centers help to reduce the burning of the residues and create value for waste that would otherwise go unused and allow the demand side to guarantee the supply of biomass and are one of the key proximity responses for small producers or landowners (CBE - Centro da Biomassa para Energia, 2021). The creation of these centers can be a good opportunity for waste producers, recovery companies, and municipalities, but it is necessary to ensure that these parks are built in appropriate locations, with the quantity of waste that justifies their construction, otherwise, they will not be economically viable. For this to be possible, in addition to municipal involvement, political and legislative involvement is also essential, which, in the eyes of those surveyed, has not been enough. Incentive policies are essential in this regard, and the government must set an example in terms of both biomass valorization and forest management. These incentive policies should be aimed at both industry and business and the end consumer, thus aligning the entire RAFB value chain. The questionnaire revealed that there is support from the PRR for the installation of waste collection parks. Measures that enable the design of more efficient and sustainable supply chains and where the added value of biomass occurs earlier are essential (Singhvi and Gokhale, 2019). In this sense, and in addition to some of the measures already mentioned, the promotion of a distribution system for decentralized and portable shredders, associated with transport systems with compaction, would facilitate the transport of biomass, which is one of the most complicated activities within the whole chain (Bioenergia em Portugal, 2023). These types of measures involve partnerships between municipalities, agricultural producers, valorization companies, and agroforestry associations.

4.7. Discussion

Although numerous scientific studies have used MCDM methods to prioritize alternatives using decision criteria, there is little work that integrates these methods with the roadmapping technique. This work proposes a model that integrates, for the first time, the PROMETHEE II decision method with the roadmapping technique. As mentioned in other studies integrating the roadmapping process with MCDM, it is necessary to give the roadmapping process dynamic and flexible characteristics and this can be achieved by integrating MCDM with roadmaps (Matani et al., 2019). The proposed model does not alter the traditional proposals for developing roadmaps but complements them by adding a mathematical basis, which means that merely descriptive roadmaps are surpassed. One of the advantages of this integration is that all respondents are considered equally or weighted in the development of the roadmap. It is the first time that a structured model has been developed that integrates the PROMETHEE model with the roadmapping technique, and it is the first time that a phase is presented in the construction of the model where it is explained how the results obtained through the PROMETHEE II model should be introduced into the roadmap. A study in (Ghazinoory et al., 2014) proposes a model that aims to integrate decisions into technological roadmaps, using a fuzzy-PROMETHEE combination. Although the proposed model presents five steps to follow, these steps do not include an explanation of how the prioritization of alternatives obtained should be introduced into the roadmap. Furthermore, the roadmap proposal presented in the case study, where the method is applied, does not follow a structured form such as that proposed by EIRMA and used in this work. Although the proposed model is defined in seven steps, in each of the steps there is great freedom for those responsible for developing the roadmap in question to act in different ways, considering the situation in question. This means that the model can be replicated in different situations and that there are various ways of applying it, something that was not the case in some of the cases where MCDM methods were integrated with the roadmapping process. For example, in (Jeon et al., 2011) the authors incorporate the AHP method with the roadmapping process in the semiconductor industry and one of the limitations they identify in their study is its replicability in other industries. In this case, the proposed model was used to build the technological layer of the roadmap. The same had already been done in (Matani et al., 2019). It would be interesting to apply the model to another layer of the roadmap to see its applicability and behavior or apply the model in another way, other than in a specific layer. For example, different future scenarios could be defined, and the model used to compare these scenarios. As far as the roadmap proposal is concerned, this is the first time that a roadmap has been developed in Portugal as part of the valorization of RAFB. Even when looking at the number of roadmap publications in this area, there aren't many, especially when it comes to structured roadmaps like the one presented. The roadmap developed made it possible to understand that the valorization of RAFB in Portugal involves several sectors that can be positively impacted by this valorization. The energy sector is one of them. RAFB should be used in a sustainable conjunction with other renewable energy sources to help the energy sector, both from the point of view of carbon neutrality and energy independence, to achieve some of the national and European targets in this area (Ferreira et al., 2017). Forest management is another of the great advantages of valorizing RAFB. Most fires in Portugal are caused by the high fuel load in forests. The valorization of these residues would make forests cleaner and there would be fewer rural fires (Ferreira et al., 2015). Agroforestry waste can be valorized in various ways. The most common in Portugal today is direct combustion to produce energy or heat. The most emerging technique identified in this study is gasification. It is believed that this technology, which until now has only been used in pilot projects and R&D centers in Portugal, will grow in the coming years and become commercially used. This use is mainly motivated by the production and commercialization of hydrogen. The pellet industry is also one of the main industries associated with the valorization of agroforestry residues in Portugal and it is believed that this will continue. The production of wood pellets makes it possible to add value to the residues and reduce logistical problems associated with transport and storage, which is essential when it comes to RAFB supply chains. Investment in scientific development and the dissemination of knowledge between the different involved parties is essential for the success of the RAFB valorization market. Collaboration between industry and the academic world is one of the possible ways of disseminating knowledge. Public policies and political involvement in decision-making are essential for the development of the RAFB valorization market, at national, regional, and municipal levels. Even though some progress has been done through this research, the work performed has some limitations. Although the proposed model is an advance in the literature, it can be hard to implement since it's complex and the responsible for its implementation must be knowledgeable in terms of the MCDM PROMETHEE and the development of roadmaps. Besides being complex the implementation of the proposed model is also time consuming since many steps need to be performed and they cannot be simultaneously assessed. Another limitation of the model is the need to use experts as source of information, and in some cases, there are challenges in terms of availability. When considering the case study in this case, the use of questionnaires can be a limitation, because even though it was the easiest and fastest way to contact the experts, some information can be lost. To avoid this the performance of interviews or workshops could have been done. Other important limitation is the fact that the proposed roadmap needs to be evaluated and restructured whenever necessary in the future.

5. Conclusions

Fires have become a significant global issue, and Portugal is among the European countries most affected. To combat this, effective forest management is crucial. One of the causes for intensive rural fires is the amount of biomass existing in the forest that act as fuel for fires. To remove this biomass that acts as fuel from the forest, initiatives that promote its recovery are essential and strategic plans for this sector must be performed. This study proposes a model that combines the roadmapping process with the PROMETHEE II decision-making method, applying it to the valorization of agroforestry residues in Portugal. This model is the first ever to combine the PROMETHEE decision method with the roadmapping process. The roadmap highlights several benefits from valorizing agroforestry residues, including the reduction rural fires, the increase if renewable energy alternatives, and sustainable regional development. Currently, the primary method for valorizing agroforestry residues in Portugal is combustion, which utilizes forest residues to generate electricity and heat. The pellet market, a significant user of forestry waste, is also expected to grow in the coming years. The roadmap indicates that other valorization technologies with commercial potential, such as gasification, are likely to emerge. Gasification, linked to hydrogen production, is anticipated to gain commercial traction in Portugal by 2027. Innovating in the valorization of agroforestry residues requires support for development and collaboration between public and private sectors. Rapid development is vital to prevent knowledge loss and promote sustainable regional growth. The investment in R&D through research programs that connect the industry, and the academia is essential in this sector for its sustainable development and knowledge exchange. The implementation of education programs that raise awareness among local communities about responsible agroforestry residue management should be implemented, through partnerships with municipalities. Municipalities or private entities should also offer residents help on managing their agroforestry residues. By involving all stakeholders and establishing effective public policies, Portugal can improve the management of agroforestry residues, enhance forest management, and prevent rural fires.

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CRediT authorship contribution statement

Adriana S.F. Alves: Writing – original draft, Visualization, Validation. **Leonel J.R. Nunes:** Writing – review & editing, Validation, Data curation. **João C.O. Matias:** Supervision, Project administration, Funding acquisition. **P. Espadinha-Cruz:** Validation, Software, Formal analysis, Data curation. **Radu Godina:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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