

The exposure of nonhuman living organisms to mobile communication emissions: A survey to establish European stakeholders' policy option preferences

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Abstract

There is an unprecedented exposure of living organisms to mobile communications radiofrequency electromagnetic field (RF-EMF) emissions. Guidelines on exposure thresholds to limit thermal effects from these emissions are restricted to humans. However, tissue heating can occur in all living organisms that are exposed. In addition, exposure at millimetric frequencies used by 5G may impact surface tissues and organs of plants and small-size species. It is also expected that the addition of 5G to existing networks will intensify radiofrequency absorption by living organisms.

A European Parliament report proposed policy options on the effects of RF-EMF exposure of plants, animals, and other living organisms in the context of 5G: funding more research, implementing monitoring networks, accessing more information from operators on antennas and EMF emissions, and developing compliance studies when antennas are installed. However, there is no evidence on the preferences of relevant stakeholders regarding these policy options. This paper reports the findings of a survey of key European stakeholders' policy option preferences based on the European Parliament's report. It reveals a broad consensus on funding more research on the effects of exposure of plants, animals, and other living organisms to EMFs. It also highlights the need for deliberation concerning the other policy options that could provide solutions for regulatory authorities, central administrations, the private sector, nongovernmental associations and advocates, and academics. Such deliberation would pave the way for effective solutions, focusing on long-term output from funding research, and enabling short-term socially and economically acceptable actions for all parties concerned.

KEYWORDS

5G, birds, electromagnetic fields, insects, legislation, multiple-criteria decision-making, plans, wildlife

1 | WHY FOCUS ON THE EFFECTS OF MOBILE COMMUNICATION EMISSIONS ON NONHUMAN ORGANISMS?

There is an increased exposure of living organisms to ubiquitous man-made electromagnetic field (EMF) emissions, primarily due to the introduction of mobile communications under the so-called "radio-frequency electromagnetic fields" (RF-EMF) (Levitt et al., 2021a).¹ The levels of exposure at

mobile communications frequencies have steadily increased over time (Bandara & Carpenter, 2018), mainly explained by the communications from outdoor mobile phone base stations toward users (Sagar et al., 2018). Mobile communications emissions below 300 gigahertz are classified as nonionizing radiation, and unlike ionizing radiation from sources such as nuclear power plants or radon, they are not identified as carrying enough energy to break atomic bonds leading to changes that are potentially carcinogenic and mutagenic (Karipidis et al., 2021).² There is nevertheless

¹ RF-EMF lie in the frequency range between 100 kilohertz and 300 gigahertz and includes mobile phones, wireless networks such as Wi-Fi, and also radio and television broadcasting, cordless phones, police and fire department radios, point-to-point links and satellite communications, among other services.

² The International Agency for Research on Cancer (IARC) classified electromagnetic fields from mobile communications as possibly carcinogenic to humans (Group 2B) (IARC, 2011). This category denotes a credible causal association that does not rule

well-established evidence of tissue heating from short-term acute exposure to these emissions (EPRS, 2021; ICNIRP, 1998, 2020; Pophof et al., 2022a).

From a regulatory perspective, current guidelines on exposure thresholds to limit thermal energy from mobile communications emissions developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and by the Institute of Electrical and Electronics Engineers (IEEE) only concern human health (ICNIRP, 1998, 2020; IEEE, 1991, 2019).³ It is worth noting that ICNIRP and IEEE thresholds, developed under the assumptions that biological effects are due to excessive tissue heating and that no effects occur below the threshold, remain controversial (ICBE-EMF, 2022). According to the International Commission on the Biological Effects of Electromagnetic Fields (ICBE-EMF), adverse effects have been observed below the threshold, such as nonthermal induction of reactive oxygen species, DNA damage, cardiomyopathy, carcinogenicity, sperm damage, and neurological effects (e.g., electromagnetic hypersensitivity).

Although the thresholds implemented in some countries are stricter than those defined by ICNIRP and IEEE guidelines, compliance solutions for mobile phone base stations are similar across European countries.^{4 5} Operators are required to define exclusion zones around their mobile phone base stations prior to installation, to ensure compliance with regulatory limits on human exposure (ITU, 2018; Lewicki, 2020). Operators can also choose to decrease the maximum transmission power of the mobile base station, as well as to change other technical parameters or even relocate the antenna (GSMA, 2014; PWC, 2013).

The ICNIRP has worked under the general assumption that nonhuman organisms are protected from harmful RF-EMF radiations as long as humans are protected (ICNIRP, 2000). However, no regulation is currently applied to protect nonhuman organisms in areas with high exposure (Levitt et al., 2021a). Flying species such as birds, bats, and insects can approach mobile antennas closer than can humans, and there is no control on the location of antennas with respect to plant species and nesting habitats of animals (WHO, 2022). Moreover, the evidence shows that mobile communication emissions can cause thermal heating not just only in humans but also in plants, animals, and other living organisms (EPRS, 2021).⁶ Nevertheless, for a given frequency, the absorbed

power and thermal induction depend on the type of living organism, because these effects are determined by the organism's size, morphology, dielectric and thermal properties, and thermoregulation (EPRS, 2021; Pophof et al., 2022a). For instance, plants maximize their surface-to-volume ratio to optimize their interaction with the environment, and hence they are specially adapted to absorb EMF emissions (Vian et al., 2007). Moreover, as plants lack mobility, they can be constantly exposed in a radiated area.

Small-size animals are also particularly sensitive to frequencies above three gigahertz, which will be increasingly used for new generations of communication, because resonance factors that can lead to significant heating are size dependent (De Borre et al., 2021; Simkó & Mattsson, 2019; Thielens et al., 2018). In such cases, small shifts of incident power density to these higher carrier frequencies can increase the insects' absorbed power by a relatively large factor (Thielens et al., 2020). Furthermore, the exposure of plants to EMFs at millimeter wavelengths (e.g., in the 26 gigahertz band) should receive special attention because they can impact tissues and organs that have a high surface area-to-volume ratio (e.g., leaves) (Vian et al., 2016).⁷ In sum, given the absence of relevant regulations and guidelines, non-human organisms can also be exposed to man-made EMFs at thermal levels. Flying animals and plants located within exclusion zones surrounding mobile phone base stations or between two connected radio relay antennas are especially at high risk of such exposure. It is worth noting that exclusion zones with no public access around the mobile phone base stations are widening when 5G technology involves adding new emissions to a mast with preexisting emissions based on older technologies (ITU, 2018; Lewicki, 2020).

The onset of 5G technology has reopened the debate on the effects of EMFs on health in the public sphere. 5G technology is commonly associated with the use of multiple-input multiple-output (MIMO) antennas, new frequency bands above 6 gigahertz, and small cells (ITU, 2021).⁸ The effects on human health due to the exposure associated with these antennas, and with millimetric frequency bands such as the 26 gigahertz band are yet to be fully explored (ANSES, 2022).⁹ Within the context of the arrival of this technology, a report was commissioned by the Panel for the Future of Science and Technology (STOA) and managed by the European Parliamentary Research Service (EPRS) to review the academic literature on the effects of RF-EMFs used in 5G technology on nonhuman vertebrates, invertebrates, and plants (EPRS, 2021). The report proposes a set of policy options that address the problem of the potential effects of EMFs from mobile communications on nonhuman organisms.

out bias or confounding factors with reasonable confidence. There is so far limited evidence for the carcinogenicity of electromagnetic fields exposure to humans at mobile communications frequencies and research is still ongoing on the topic (IARC, 2013).

³ The ICNIRP is an international nongovernmental organization bringing together independent scientific experts. The IEEE is a technical professional organization dedicated to advancing technology. ICNIRP and IEEE guidelines are relatively similar (ITU, 2021).

⁴ At least 30 countries across the world have chosen to implement more restrictive human exposure thresholds than those defined by ICNIRP and IEEE guidelines since the onset of mobile communications in the 2000s (ITU, 2017; Madjar, 2016; Stam, 2018; WHO, 2017).

⁵ Exposure to emissions from mobile handsets (Deruyck et al., 2021) is out of the scope of this article because this type of exposure is not relevant for nonusers such as plants and animals.

⁶ Other biological effects of artificial RF-EMFs in nonhuman organisms have been well documented (see Appendix 1 for a detailed discussion).

⁷ These wavelengths can also impact the morphogenesis of plants if organs are developed as an electromagnetic dielectric resonator (Pietak, 2012).

⁸ The international guidelines for human health have been updated to take into account the specificities of emissions in the new frequency bands and of 5G technology (ICNIRP, 2020; IEEE, 2019).

⁹ Besides, the use of averaged exposures to antenna phased arrays based on international standards may overlook the biological exposure to peak waves (Levitt et al., 2022).

This article is based on the conclusion drawn from the EPRS review, through a survey of a representative sample of interest groups and interviews with selected stakeholders in Europe. It aims to identify policy priorities among those proposed by the EPRS report. The analysis uses a multicriteria decision-making (MCDM) model that has been applied to an array of risk-based problems (Keisler & Linkov, 2021). In particular, an integrated Analytic Hierarchy Process-Goal Programming (AHP-GP) approach is implemented. Both AHP and GP apply to a variety of situations involving risk and uncertainty in governmental planning (Rakes et al., 2022; Saaty, 1987). This integrated approach enables the user to identify compromise solutions and is therefore useful for politically sensitive situations or situations where different stakeholders have highly divergent preferences. The derived results can be used to develop priority pilot programs on the topic of EMFs.

The remaining sections of this article are set out as follows. The second section describes the policy options proposed by the EPRS to prevent the exposure of nonhuman organisms to mobile communications emissions (EPRS, 2021). The third section presents the survey-based methodology to analyze the preferred EPRS policy options by different stakeholder groups. The fourth section reports the results of the survey analysis. The fifth section discusses some policy implications. The [appendix](#) contains complementary information about the survey and the methodology used in this article.

2 | WHICH POLICY OPTIONS FOR EXPOSURE OF NONHUMAN ORGANISMS TO MOBILE COMMUNICATION EMISSIONS WERE PROPOSED BY THE EPRS?

The EPRS report concluded that dielectric heating can occur at all frequencies used by mobile communications (0.4–300 gigahertz) and for all living organisms. Besides, research on vertebrates has often mixed or inconclusive results.¹⁰ Concerning invertebrates and plants, research is lacking and is very limited for frequencies above 6 gigahertz. Given the results of the analysis, the report proposes four policy options that are described as follows.

The first policy option is to fund research on the exposure of nonhuman organisms to RF-EMF. In particular, the EPRS proposes to fund research on RF-EMF exposure of plants, fungi, and invertebrates at frequencies below 6 gigahertz, and all nonhuman organisms at frequencies above 6 gigahertz, as below 6 gigahertz, most studies have been developed for vertebrates. Moreover, although there are only a few studies above 6 gigahertz across all taxa, these frequencies are already in use by 5G and are expected to be increasingly employed using this technology. Such research would allow

for the implementation of evidence-based policy measures concerning the exposure of nonhuman organisms to RF-EMF. The EPRS report recalls that the ICNIRP guidelines that are currently used in most European countries take into account the biological effects that are harmful to human health only (ICNIRP, 1998, 2020).

The second policy option is to measure and monitor the exposure of nonhuman organisms to environmental RF-EMF, that is, their exposure to far-field sources because nonhuman organisms are nonusers of technology. These measures and monitoring should take place in locations where plants and animals are more prevalent, unlike current practices that focus on human presence. Because measurements require trained technicians and are time-consuming, they could be replaced by monitoring networks that provide temporal information without requiring an on-site technician.

This second option is relevant in assessing whether precautionary measures should be implemented to protect nonhuman organisms from exposure to RF-EMF. Indeed, there is a need to initially prove that the exposure has a negative effect or that there is uncertainty. In the case of RF-EMF, given the limited literature on certain categories of organisms, there is uncertainty about the effects of exposure. Second, there must be a risk of (significant) exposure. Although exposure is expected to change with 5G technology, it is difficult to predict it now with the limited deployment of this technology.

The third policy option is to make it compulsory for operators to share information on mobile base station antennas, as these are the dominant sources of environmental RF-EMF. Operators could disclose data on the type of antenna, the operation frequencies, the precoding used over time, the output power over time, and the specifications of the antenna installation. This information is necessary to calculate retroactively environmental RF-EMF exposure over time at a large scale, but it is often not available, as operators are wary of sharing their technical know-how. An alternative would be to establish an independent committee that could interpret the data, instead of disclosing the information publicly.

The fourth option is to require compliance studies for nonhuman organisms when mobile phone base station antennas are installed. These studies would enable competent authorities to determine the exposure of an organism near the antenna, the maximum output power from the antenna, and the minimum separation distance between the antenna and the organism. Compliance studies should be implemented for all organisms likely to be in the vicinity of the antenna, given that dielectric heating has been demonstrated for all the categories of organisms included in the EPRS report. This typically includes bats, birds, insects, and nearby plants. These compliance studies are essential, as those currently implemented within ICNIRP guidelines focus only on human organisms. However, the relationship between RF-EMF exposure and temperature increase is determined by the properties of the organism and, hence, in characteristics such as surface-to-volume ratios, dielectric properties, thermal properties, thermoregulation capacity, and physical size.

¹⁰ See Appendix 1 for a short discussion on the limitations concerning the research on the effects of RF-EMFs in nonhuman organisms.

3 | THE DATA AND METHODOLOGY

The survey is relevant to the extent that the relevant stakeholder groups are identified, that the respondents are representative of their respective organizations, and that they are involved in policymaking in their organizations. Concerning the first two points, international and national expert meetings on health effects due to exposure to RF-EMF have been held since the 2000s, with a larger weight given to recent meetings and to those meetings with a special focus on nonhuman organisms. The meetings were organized by a variety of organizations, both private and public or international.¹¹ They were mostly ad hoc meetings, seminars, and conferences, rather than regular forums. The stakeholder groups were consistently present across different meetings both at the European and at the national scale.

Participants from nongovernmental associations (NGOs) (and advocates) from the RF-EMF community had often participated in RF-EMF calls for action. Participants from academia were identified by selecting the authors with high records of recent publications on the topic. They often attended the meetings previously described and have sometimes participated in calls for action on RF-EMF. Participants from NGOs from the environmental community were identified by selecting the most important conservation organizations working with some species that are potentially sensitive to the exposure to RF-EMF (bats, birds, bees), and which can be subject to high exposure levels as they can get close to antennas. Overall, the selected participants are typically involved in policymaking on RF-EMF at their respective organizations, by directly contributing to the elaboration of documents to define or influence policymaking, guidelines, standards, and recommendations, or by providing input to feed in these streams of work. The choice of the interest groups takes, therefore, into account those stakeholders currently involved in decision-making processes on RF-EMF. Nevertheless, some participants may lack appropriate expertise on the environmental risk of RF-EMF to nonhuman organisms and, more generally, to life sciences. Through the survey, both the strengths of this range of stakeholders and their limitations are put to the forefront in a topic that is inherently of a transdisciplinary nature and calls for a close collaboration between the different disciplines given the complementary required expertise.¹²

The online survey was composed of two parts. First, the survey contained an introduction to explain the framework and to describe the main policy options identified by the EPRS report (Appendix 2). Second, the survey itself was

composed of the core question on policy priorities concerning the exposure of nonhuman organisms to RF-EMF from mobile networks. This question was preceded by two additional questions to identify the typology of the respondents (Appendix 3). In particular, the respondents were requested to select the main stakeholder group to which they belonged, as well as the country where the institution they worked for was located. Respondents were requested to submit their individual views and not those of the country or institution they represented. They were informed that personal information would not be disclosed.¹³

The survey was used to prioritize decision-making alternatives involving multiple social groups and multiple goals, by searching for compromise consensus under an MCDM methodology.¹⁴ There are five predefined policy options (Table 1). A policy option on “no action” was added to the four policy options identified by the EPRS report for completeness. There are also six predefined groups of stakeholders:¹⁵ (1) regulatory agencies, (2) central administrations, (3) the private sector, (4) NGOs and advocates, (5) academics, and (6) local administrations.¹⁶

The analysis is based on the assumption that it is highly unlikely that two or more options are selected at a national scale or the European level, given that (i) humans have so far chosen not to address the effects of RF-EMF on nonhuman organisms even if there is evidence of thermal effects on all living organisms; and (ii) any of the proposed “action” measures (options 1–4 in Table 1) have associated costs borne by the public sector and/or the private sector, and with potential direct and/or indirect economic impacts through mobile sector activities. The degree of conflict between the options can be derived through a payoff matrix constituted by optimizing each of the options in Table 1 separately over a constraint set and then estimating the value of the other options at

¹³ As a follow-up to the survey, respondents were contacted to identify their main field of expertise (i.e., studies completed on engineering, physics, life sciences, social sciences, etc).

¹⁴ Equal weight has been applied to the different stakeholder groups. First, stakeholder groups have not devoted in the past significant attention to the topic of the effects of the exposure of nonhuman organisms to RF-EMF. Second, the past dynamics between the different stakeholders on the protection of human from the exposure to RF-EMF uncover a playing field whereby it is difficult to predict policy outcomes. The weight of civil society on the policy debate led to unpredictable policy outcomes in the 2000s. As such, a certain number of European countries have chosen exposure limits that are more constraining than those defined by ICNIRP or IEEE guidelines. With the advent of 5G, national administrations have faced uncertainty regarding their capacity to authorize 5G emissions. Beyond these considerations related to whether or not giving the same weight to all stakeholder groups is realistic, the analysis targeted a normative outcome (value-based perspective of what “should” be), rather than a positive outcome associated with what the market will actually deliver.

¹⁵ The stakeholder groups are intended to represent the different viewpoints of the society at large, and as such they were chosen for this survey. Note that surveys targeting directly the population could elicit the preferences of the society concerning this topic according to their valuation, but this remains beyond the scope of this article.

¹⁶ Although local administrations are relevant stakeholders regarding RF-EMF policies, they remain out of the scope of this article as their views cannot be appropriately captured through this type of survey at the European scale. Indeed, local administrations were initially contacted to complete the online survey through national associations of local administrations, e.g., the Council of European Municipalities and Regions (CEMR) and Mayors of Europe. The rate of response was very low and failed to reflect nationwide plurality. Additional research on the views of this stakeholder group would be informative to complement the work implemented in this article.

¹¹ These meetings were organized by organizations such as the Body of European Regulators for Electronic Communications (BEREC), the Radio Spectrum Policy Group (RSPG), the ICNIRP, the WHO, the BFS, the Global System for Mobile Communications (GSMA), and the International Telecommunications Union (ITU).

¹² For example, engineers may have relevant expertise on benefits and limitations associated with RF-EMF monitoring, social sciences’ experts from NGOs in the RF-EMF community are likely to be well aware of decision-making dynamics, and life sciences’ experts from NGOs in the biodiversity community are likely to have a holistic understanding of nonhuman species legal frameworks, ecological stressors, and effectiveness of potential management solutions.

TABLE 1 Policy options concerning exposure of nonhuman organisms to RF-EMF from mobile networks.

Designation	Description
O_1	Funding research on exposure to nonhuman organisms o RF-EMF
O_2	Monitoring RF-EMF exposure on nonhuman organisms
O_3	Information sharing on base station antennas by mobile operators to assess exposure
O_4	Compliance assessments and prevention of high RF-EMF exposure near base station antennas for nonhuman organisms
O_5	No action

Note: Options are detailed in Section 2 and Appendix 2.

TABLE 2 Payoff matrix to derive the degree of conflict between options.

Optimization option	Values for the different options				
	Funding research	Monitoring RF-EMF exposure	Information on base station antennas	Compliance assessments and prevention	No action
Funding research	Max	Min	Min	Min	Min
Monitoring RF-EMF exposure	Min	Max	Min	Min	Min
Information on base station antennas	Min	Min	Max	Min	Min
Compliance assessments and prevention	Min	Min	Min	Max	Min
No action	Min	Min	Min	Min	Max

Note: The elements of the main diagonal (bold) represent the ideal values when the corresponding option is maximized. The lowest values of each of the columns represent the corresponding undesirable outcome for that option.

each of the optimal solutions (Linares & Romero, 2000). In the absence of precise estimates to derive this matrix, it is possible to implement a qualitative analysis (see Table 2).

Proceeding to analyze the payoff matrix, once the no-action option (option 5) is maximized, the remaining options are minimized. The analysis concerning the other options is more subtle. If we maximize the funding research option (option 1), this may probably lead to higher taxation on mobile operators and management burden on the public sector. There is a modest probability that additional requests concerning options 2–4 are accepted because they would also place a burden on the private and public sectors. In addition, like option 1, options 2–4 can impact mobile rollout through taxation, communication, and/or deployment restrictions. To summarize, once the funding option is maximized, the probability that the remaining options are chosen is minimized. The other options (2–4) in Table 2 can be analyzed following the same reasoning.

Furthermore, it is possible to implement options 1–4 independently. For instance, options 2 and 4 can be considered independently of option 1 on funding research. Option 2 on monitoring can be developed with currently prevailing methods and technologies. Option 4 on compliance assessments and prevention can be implemented based on the evidence associated with the thermal effects of the exposure to RF-EMF and using current simulation and measurement techniques. The prevention of exposures can also be done using existing technologies, for example, radomes, wires, nets, and plastics, as this is currently done for radar technologies. It is also possible to develop research studies without data from monitoring networks and disassociated from compliance assessments.

Based on the framework laid out above, there is a significant degree of conflict between the five options. There are no redundant options and consequently all options should be considered in the analysis. In fact, whereas respondents were allowed to give equal priority to options 1–4, none chose this possibility. Nevertheless, although the options analyzed are currently considered mainly exclusive, this may evolve toward more complementarity with stronger support for action. For example, monitoring networks and information from base station antennas can feed into research analyses, research studies could provide new evidence (e.g., related to nonthermal effects of exposure to RF-EMF), which can be used in compliance assessments and prevention measures.

This MCDM methodology is based on an integrated AHP-GP¹⁷ approach involving multiple objectives that can be conflicting (Ananda & Herath, 2009).¹⁸ Within this framework, the AHP enables preferential weights for each group of decision-makers to be obtained that can be used as input for the compromise GP method to obtain societal preferences. In the first stage of the approach, the AHP is used to evaluate the relative importance of the policy options in Table 1 at the level of stakeholder groups (Saaty, 1990). The AHP has typically four phases: (i) modeling, (ii) valuation, (iii) prioritization, and (iv) synthesis. Given the one-level modeling presented in Table 1, each respondent was requested to perform paired comparisons of policy options, taking into account their relative importance to form a pairwise matrix. The respondent

¹⁷ It is recalled that AHP-GP stands for Analytic Hierarchy Process-Goal Programming.

¹⁸ The integrated AHP-GP combines two of the most common MCDM techniques. This approach is often used in operations research (see, for instance, Aznar-Bellver et al., 2011; Díaz-Balteiro & Romero, 2001; Khorramshahgol & Al-Husain, 2021).

TABLE 3 The comparison scale to evaluate policy options concerning RF-EMF exposure to nonhuman organisms from mobile networks.

Explanation of the comparison scale	Numeric values to enter
If option O_i and O_k are EQUALLY important	0
If option I is MODERATELY more important than option O_k	3
If option I_i is STRONGLY more important than option O_k	5
If option I is VERY STRONGLY more important than option O_k	7
If option O_i is EXTREMELY more important than option O_k	9

Note: O_i and O_k represent the different options in Table 1 where $i = 1, \dots, q$ and $k = 1, \dots, q$ with $k \neq i$ and $q = 5$.

was asked to use a modified Saaty scale from zero to nine (Table 3).¹⁹

In the third AHP phase, the weights associated with the different policy options were derived from the pairwise matrix for each respondent through the eigenvalue method (Goepel, 2013; Larsen, 2013). A key feature of the AHP is the possibility to evaluate the inconsistency of each respondent when eliciting its choice through a consistency ratio (CR) that should typically be below or equal to 10% (Saaty, 1990).²⁰ If the CR is above 10%, inconsistent rating of policy options was corrected by exchanging with the respondent and/or correcting mistakes in the data, to obtain $CR \leq 10\%$.

In the fourth phase (synthesis), the final weights associated with the group of stakeholders were derived by aggregating the weights of each respondent within that group through the geometric mean aggregation method because it can preserve the reciprocal property in the combined pairwise comparison matrix (Liu et al., 2017). A Shannon-entropy consensus indicator for the aggregated stakeholder group result was also derived (Shannon, 1948).²¹ The indicator ranged from 0% to 100% consensus, with intermediate values indicating the degree of consensus between respondents within the same stakeholder group.²²

In the second stage of the AHP-GP approach, an extended GP method was used to aggregate the weights attributed to policy options by each group of stakeholders (Linares & Romero, 2002; Romero, 2014). The method enables the user to integrate minority choices by developing solutions where more importance is attached to the minority stake-

holder group, that is, the group whose judgment significantly differs from the choices of other groups. The method can provide social weights that minimize the disagreement of the most displaced stakeholder group. The achievement function associated with this method is as follows:

Achievement function:

$$\text{Min } (1 - \lambda) D + \lambda \sum_{i=1}^q \sum_{j=1}^m (\bar{n}_{ij} + \bar{p}_{ij}) \quad (1)$$

such that
Goals:

$$\sum_{i=1}^q (\bar{n}_{i1} + \bar{p}_{-1}) - D \leq 0 \quad (1.1)$$

...

$$\sum_{i=1}^q (\bar{n}_{im} + \bar{p}_{-m}) - D \leq 0$$

$$W_i^s + \bar{n}_{ij} - \bar{p}_{ij} = W_i^j, \quad (1.2)$$

$$i \in \{1, \dots, q\}, j \in \{1, \dots, m\}$$

Accounting rows:

$$\sum_{i=1}^q (\bar{n}_{i1} + \bar{p}_{-1}) - D_1 = 0 \quad (1.3)$$

...

$$\sum_{i=1}^q (\bar{n}_{im} + \bar{p}_{-m}) - D_m = 0$$

$$\sum_{i=1}^q \sum_{j=1}^m (\bar{n}_{ij} + \bar{p}_{ij}) - Z = 0 \quad (1.4)$$

$$\bar{n} \geq 0, \bar{p} \geq 0, \lambda \in [0, 1]$$

¹⁹ The Saaty scale was slightly modified by substituting the scale of one by a scale of zero to render the interpretation easier to respondents. Applying then a scale of zero in a pairwise comparison means attributing an equal importance to two policy options.

²⁰ The CR ranges between zero and one and is given by $CR = CI/RI$, where CI stands for the consistency index expressed as $(\lambda_{\max} - n)/(n - 1)$, $\lambda_{\max}$ being the principal eigenvalue of the matrix and n is the order of the matrix, and RI stands for the randomness index (Saaty's predefined index depending on the size of the matrix) (Saaty, 1980). If there is full consistency, $CR = CI = 0$.

²¹ The Shannon-entropy consensus indicator integrates both alpha diversity, which measures the average individual decision maker's priority distribution among policy options, and beta diversity, which measures the variations of priority distributions among decision-makers within the stakeholder group. See Goepel (2013, 2018) for a detailed description of the indicator. Building on information theory, this index has been used extensively in ecology during the last 50 years to measure biodiversity (Magurran & McGill, 2011). Note that in the presence of a large variety in dissimilar judgments, the Shannon consensus index allows to explore potential subgroups of higher consensus among a larger group of participants (Goepel, 2024). Other consensus indexes could also be applied (see, e.g., Chiclana et al., 2008; Dong et al., 2010).

²² The consensus indicator can be interpreted in the following way: very low ($\leq 50\%$), low (50%–65%), moderate (65%–75%), high (75%–85%), and very high ($\geq 85\%$) (Goepel, 2018).

where $i = \{1, \dots, q\}$ are the policy options ($q = 5$), $j = \{1, \dots, m\}$ are the stakeholder groups ($m = 5$),²³ $\tilde{n}_{ij}$ and $\tilde{p}_{ij}$ are the negative and positive deviation auxiliary variables that represent the difference between the consensus value for the i th policy option and the value attributed to the i th policy option by the j th stakeholder group, λ is a control parameter that can vary between 0 and 1, W_i^j is the preference weight attached to the i th policy option by the j th stakeholder group, W_i^s is the preference weight attached to the i th policy option criterion across all groups of stakeholders (referred to as society hereafter), $D_1, \dots, D_m$ are variables that measure the disagreement of each stakeholder group with respect to the consensus value, $D = \max(D_1, \dots, D_m)$ and $Z = \sum_{i=1}^m D_i$.

Through the achievement function (1), the societal weights W_i^s attached to each policy option are derived from the stakeholder groups' weights W_i^j attached to each policy option. For $\lambda = 0$, the function implements the minority consensus, that is, a consensus that minimizes the disagreement of the most displaced stakeholder group. For $\lambda = 1$, the function implements the majority consensus, that is, the consensus that maximizes the average agreement. For intermediate values of λ , the function implements compromise solutions between the minority and the majority consensus. The achievement function is typically run for values of $\lambda = 0$ and $\lambda = 1$ and, if necessary, for intermediate values.

4 | THE SURVEY RESULTS

The online survey was carried out between March 14 and April 31, 2023.²⁴ The survey data from 86 respondents were collected between March 14 and April 31, 2023.²⁵ The respondents worked at 75 organizations located in 22 countries in the European Union, Switzerland and the United Kingdom (Table A41 in Appendix 4).²⁶ There were many respondents from France (24), the United Kingdom (10), Germany (6), Italy (6), and Switzerland (5).²⁷ In terms of the stakeholder groups, most of the regulatory agencies were

TABLE 4 Stakeholder groups.

Designation	Key stakeholders	Number of respondents	Number of countries
D_1	Regulatory agencies	24	16
D_2	Central administrations	12	7
D_3	Private sector	5	5
D_4	NGOs and advocates	26	10
	-RF-EMF community	18	9
	-Environmental community	8	3
D_5	Academics	19	9

specialized in the telecommunications sector, with a small minority handling radiation and/or health issues as their core activity. Respondents from central administrations came from a diversity of structures, ranging from ministries to specialized agencies, and with core activities ranging from economic development to health.

The private sector is composed of both operators and manufacturers. NGOs and advocates represented the RF-EMF area of expertise and, to a lesser extent, the environmental field (bat, bird, and bee conservation).²⁸ NGOs from the environmental field had not necessarily been involved with RF-EMF issues previously, unlike the other respondents of the survey. They were selected to elicit any emerging trend on RF-EMF effects concerning flying animals which are more likely to be in close proximity to the beam of the antennas (Section 2). The fields of expertise of academics were mainly engineering, medicine, and biology.

As described in Table 4, the number of respondents from regulatory agencies was particularly high (24), and they represented 16 countries (see also Table A42, which shows the countries included per stakeholder group). There was a small number of respondents from the private sector. The main field of expertise of almost half of the respondents was engineering, followed by life sciences, social sciences, and physics (Table A43). Engineers were present across all the stakeholder groups and were the majority in regulatory agencies (more precisely, 81% of respondents in regulatory agencies). Life science experts were mainly present in the NGOs and advocates and the academics stakeholder groups.

4.1 | Results from the first stage of the AHP-GP approach

In Table 5, the results of the first stage of the AHP-GP approach are presented after correcting for inconsistency in

²³ It is recalled that although the predefined number of stakeholder groups was six, local administrations were dropped from the analysis (see footnote 11).

²⁴ A pilot survey was tested with a limited number of stakeholders prior to the launch of the survey. This survey was complemented with information from semistructured interviews with selected stakeholders.

²⁵ When performing a survey, the objective is to obtain representative data within a certain target group or population. Given the initial population space (250), a desirable sample size has been attained (95% confidence level, 8.6% margin of error, and sample proportion of 50%) (Daniel, 1999; Krejcie & Morgan, 1970). The response rate is 34.4%.

²⁶ There is no overrepresentation of organizational entities as, except for respondents from regulatory agencies, in only 4 cases there are two respondents from the same institution. In the case of regulatory agencies, given the concentration of regulatory power, there are sometimes several participants from the same institution (2 in Finland, 4 in France, and 2 in Malta). Note that these institutions are often composed of departments with different mandates (e.g., international affairs, frequency management, competition policy...), and having several respondents from the same institution allows to capture this diversity.

²⁷ It is important to have survey participants from a large number of European countries because the purpose of the article is to share some insights about the preferences of European stakeholders concerning the EPRS (2021) policy options. These insights can provide some input to feed into discussions associated with the potential implementation

of these options in Europe. We note that one of the limitations of the analysis is the uneven number of respondents from different European countries (see Table A41; in particular, 40 respondents from France and 10 from the United Kingdom).

²⁸ Respondents were asked after the survey whether they agreed to disclose if they were primarily in an EMF-related community or in a biodiversity-related community.

TABLE 5 AHP results: Preferred policy options concerning exposure of nonhuman organisms to RF-EMF mobile networks according to the stakeholders' group.

	Regulatory agencies	Central administrations	Private sector	NGOs, advocates	NGOs and advocates RF-EMF community	NGOs and advocates Environmental community	Academics
Funding research	25.6	40.5	38.1	38.5	39.1	38.5	38.7
Monitoring RF-EMF exposure	21.0	17.0	19.3	20.8	22.0	18.8	25.3
Information on base station antennas	22.9	19.1	11.2	12.2	10.4	16.3	14.3
Compliance assessments and prevention	25.0	14.3	9.9	24.3	24.0	22.6	18.0
No action	5.5	9.1	21.5	4.2	4.5	3.8	3.7
Shannon-entropy consensus	62.3	44.6	46.3	62.2	56.9	64.8	68.7

Note: The table presents AHP results after correcting inconsistent ratings of policy options ($CR \leq 10\%$) (in percentage). The results are derived according to the methodology described in Section 3 (Goepel, 2013). Each of the columns adds up to 100%.

each respondent's choices.²⁹ The results are very close to those obtained without this correction (Table A44). The preferred policy option, independent of the stakeholder group, is funding research. In addition, funding research was selected as a first policy option by most respondents across all stakeholder groups (Table A45). Following funding research, the second policy option that respondents preferred was: compliance assessments and prevention (regulatory agencies, and NGOs and advocates), information on base station antennas (central administrations), no action (private sector), and monitoring RF-EMF exposure (academics).

Regarding the policy option that was selected as a first option, funding research (selected by respondents on 42 occasions) is followed by monitoring RF-EMF exposure (24), compliance assessments and prevention (16), information on base station antennas (14), and no action (4).

In Table 5, it should be noted that no action taken is by a large margin the least preferred policy option across all the stakeholder groups, except the private sector. Respondents from regulatory agencies had similar preferences across all options except for no action. Operators and NGOs and advocates attributed low values to information on base station antennas, and operators to compliance assessments and prevention.

Moreover, the Shannon-entropy consensus is relatively low for two groups of stakeholders: central administrations and the private sector. With respect to central administrations, this result can be explained by the very different nature of the concerned administrations and associated staff ranging from economic development, health, and environmental administrations to technical bodies on telecommunications, radiation, and health. Regarding the private sector, the very low consensus is more likely related to the different perceptions of these respondents concerning this topic.

In Table A46, the results of the first stage of the AHP-GP approach are presented according to a classification by

the main field of expertise of the respondent (after correcting for inconsistency in each respondent's choices). Given the typology of respondents, fields of expertise were classified as follows: engineering, physics, life sciences (mainly biology and medicine), and social sciences. The purpose of this exercise was to elicit whether there are specific patterns in choices depending on the field of expertise. A casual look at Table A46 shows that respondents have similar preferences independently of the field of expertise: funding research, followed by monitoring RF-EMF exposure, compliance assessments and prevention, information on base station antennas, and no action. Most respondents have expertise on engineering (40), followed by life sciences (24), social sciences (14), and physics (6) (Table A47). There were a larger number of engineering and life sciences respondents selecting compliance assessments and prevention as a first policy option rather than monitoring RF-EMF exposure.

The decision to break out the stakeholder groups was driven by the results in this section, despite the low number of respondents for some groups such as the private sector, and NGOs and advocates in the environmental community. From a policy perspective, it is informative to disclose group preferences. To begin with, the first choice concerning policy priorities is more funding for research independently of the stakeholder group being analyzed. This is a key output of the analysis because all the groups have the same preferences even though they have very different points of view and expertise on the topic. Moreover, by disclosing the information by stakeholder group, it is not possible to infer that these results are broadly driven by some stakeholder groups.

Secondly, there are specificities associated with each stakeholder group that can be informative for policy decisions. The preferences of the different stakeholder groups associated with monitoring RF-EMF exposure suggest that there is room for discussion for the implementation of this option. Regarding compliance assessments and prevention, both the private sector and central administrations give low ratings suggesting that any associated policy action would be difficult to implement. Probably associated with different reasons (see Appendix 5), both the private sector and

²⁹ The comments shared by the different stakeholder groups are available in Appendix 5. These comments provide anecdotal evidence and do not represent an exhaustive overview of the views of each group.

TABLE 6 Social preferences with the extended GP model.

Achievement function			
Min $(1 - \lambda)D + \lambda \sum_{i=1}^5 \sum_{j=1}^5 (\bar{n}_{ij} + \bar{p}_{ij})$			
subject to:			
Goals			
$\sum_{i=1}^5 (\bar{n}_{i1} + \bar{p}_{-1}) - D \leq 0$	$W_1^s + \bar{n}_{11} - \bar{p}_{11} = 25.6$	$W_2^s + \bar{n}_{21} - \bar{p}_{21} = 21.0$	
$\sum_{i=1}^5 (\bar{n}_{i2} + \bar{p}_{-2}) - D \leq 0$	$W_1^s + \bar{n}_{12} - \bar{p}_{12} = 40.5$	$W_2^s + \bar{n}_{22} - \bar{p}_{22} = 17.0$	
$\sum_{i=1}^5 (\bar{n}_{i3} + \bar{p}_{-3}) - D \leq 0$	$W_1^s + \bar{n}_{13} - \bar{p}_{13} = 38.1$	$W_2^s + \bar{n}_{23} - \bar{p}_{23} = 19.3$	
$\sum_{i=1}^5 (\bar{n}_{i4} + \bar{p}_{-4}) - D \leq 0$	$W_1^s + \bar{n}_{14} - \bar{p}_{14} = 38.5$	$W_2^s + \bar{n}_{24} - \bar{p}_{24} = 20.8$	
$\sum_{i=1}^5 (\bar{n}_{i5} + \bar{p}_{-5}) - D \leq 0$	$W_1^s + \bar{n}_{15} - \bar{p}_{15} = 38.7$	$W_2^s + \bar{n}_{25} - \bar{p}_{25} = 25.3$	
$W_3^s + \bar{n}_{31} - \bar{p}_{31} = 22.9$	$W_4^s + \bar{n}_{41} - \bar{p}_{41} = 25.0$	$W_5^s + \bar{n}_{51} - \bar{p}_{51} = 5.5$	
$W_3^s + \bar{n}_{32} - \bar{p}_{32} = 19.1$	$W_4^s + \bar{n}_{42} - \bar{p}_{42} = 14.3$	$W_5^s + \bar{n}_{52} - \bar{p}_{52} = 9.1$	
$W_3^s + \bar{n}_{33} - \bar{p}_{33} = 11.2$	$W_4^s + \bar{n}_{43} - \bar{p}_{43} = 9.8$	$W_5^s + \bar{n}_{53} - \bar{p}_{53} = 21.5$	
$W_3^s + \bar{n}_{34} - \bar{p}_{34} = 12.2$	$W_4^s + \bar{n}_{44} - \bar{p}_{44} = 24.4$	$W_5^s + \bar{n}_{54} - \bar{p}_{54} = 4.2$	
$W_3^s + \bar{n}_{35} - \bar{p}_{35} = 14.3$	$W_4^s + \bar{n}_{45} - \bar{p}_{45} = 18.0$	$W_5^s + \bar{n}_{55} - \bar{p}_{55} = 3.7$	
Accounting rows			
$\sum_{i=1}^5 (\bar{n}_{i1} + \bar{p}_{-1}) - D_1 = 0$		$\sum_{i=1}^5 (\bar{n}_{i5} + \bar{p}_{-5}) - D_5 = 0$	
$\sum_{i=1}^5 (\bar{n}_{i2} + \bar{p}_{-2}) - D_2 = 0$			
$\sum_{i=1}^5 (\bar{n}_{i3} + \bar{p}_{-3}) - D_3 = 0$			
$\sum_{i=1}^5 (\bar{n}_{i4} + \bar{p}_{-4}) - D_4 = 0$		$\sum_{i=1}^5 \sum_{j=1}^5 (\bar{n}_{ij} + \bar{p}_{ij}) - Z = 0$	

Note: See Section 3 for the definition of these variables.

TABLE 7 Results: Social preferences with the extended GP method.

Z	D	D ₁	D ₂	D ₃	D ₄	D ₅	W ₁ ^s	W ₂ ^s	W ₃ ^s	W ₄ ^s	W ₅ ^s
Majority consensus ($\lambda = 1$)											
92.10	29.20	28.70	17.90	29.20	9.80	6.50	38.50	20.80	14.30	19.00	5.50
Minority consensus ($\lambda = 0$)											
102.75	28.55	28.55	28.55	28.55	6.25	10.85	38.10	20.80	12.20	19.85	5.50

Note: This table shows the results of the GP method in Table 6. Z is the sum of D_1 – D_5 , D measures the maximum of the values D_1 – D_5 , D_1 – D_5 represent the disagreement of each group as listed in Table 4 with respect to the consensus that is obtained, and W_1^s – W_5^s are the reference weights (in percentage) attached by society to each criterion as listed in Table 1.

NGOs and advocates from the RF-EMF community have low preferences for the option of information from base station antennas. Lastly, even though NGOs and advocates in the environmental community were not systematically well informed about this topic, they have well-defined environmental management frameworks in the presence of uncertainty, and this is reflected in their answers to the survey as well as in their exchanges with authors.

4.2 | Results from the second stage of the AHP-GP approach

In the second stage of the AHP-GP approach, the preferences of the different stakeholder groups are integrated. Table 6 shows the formulation of the associated extended GP model, and Table 7 shows the results of the estimation. The second row in Table 7 corresponds to the solution that maximizes the

average agreement, and the third row corresponds to the solution that minimizes the disagreement of the most displaced group. Given that the majority and minority consensus are so close, no compromise solutions are necessary.

With the majority consensus agreement, respondents give at least two times more weight to funding research than to any other option (38.5%). The following options are monitoring RF-EMF exposure (20.8%) and compliance assessments are prevention (19%), with a slight advantage for monitoring. The options that received less weight are information on base station antennas (14.3%) and, in last place, no action (5.5%). This solution is closest to the preferences of scientists and NGOs and advocates ($D_5 = 6.5$ and $D_4 = 9.8$, respectively). The private sector is the stakeholder group characterized by the largest disagreement with respect to this majority consensus agreement ($D_3 = 29.2$).

Turning to the minority consensus agreement, compared with the majority consensus the sum of disagreements