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What does the public know about technological solutions for achieving carbon neutrality? Citizens' knowledge of energy transition and the role of media

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The present study explores the relation between media use and knowledge in the context of the energy transition. To identify relevant knowledge categories, we relied on the expertise of an interdisciplinary research team. Based on this expertise, we identified *awareness-knowledge of changes in the energy system* and *principles-knowledge of hydrogen* as important knowledge categories. With data obtained from a nationwide online survey of the German-speaking population (n = 2,025) conducted in August 2021, we examined the level of knowledge concerning both categories in the German population. Furthermore, we studied its associations with exposure to journalistic media and direct communication from non-media actors (e.g., scientists). Our results revealed a considerable lack of knowledge for both categories. Considering the media variables, we found only weak, and in some cases even negative, relations with the use of journalistic media or other actors that spread information online. However, we found comparably strong associations between both knowledge categories and the control variables of sex, education, and personal interest. We use these results to open up a general discussion of the role of the media in knowledge acquisition processes.

KEYWORDS

carbon neutrality, climate change, knowledge of technological solutions, energy transition, hydrogen, media use, journalistic media, online media

1. Introduction

At the heart of the current debate on global warming is the question of what can be done to avert the looming climate catastrophe. To limit global warming, it is necessary to achieve carbon neutrality as soon as possible. Carbon neutrality means that the emission of greenhouse gases into the atmosphere and their removal must be balanced. This requires a comprehensive sociotechnical transformation process in all areas, including energy supply, industrial production, transport, and people's lifestyles (Tiwari, 2021; Ragwitz et al., 2023).

With the adoption of the Federal Climate Protection Act, Germany has set its goal of achieving carbon neutrality by 2045. One important means of achieving this goal is the complete phase out of fossil fuels and a consistent switch to renewable energies. Germany laid the foundation for this transformation process in 2000, when the Renewable Energy Sources Act was enforced. The expansion of renewable energies is a central pillar of the German energy transition, also known as the "Energiewende" (for further details on the energy transition, see Quitzow et al., 2016).

However, having an entire energy system based on renewable energy sources by 2045 incurs numerous challenges. First, it requires a fundamental restructuring of the existing energy supply system, especially the expansion of renewable energy. In particular, wind power and photovoltaics must be massively increased and accelerated (Brandes et al., 2021; Ragwitz et al., 2023). Furthermore, as green electricity is produced at many scattered locations, often far away from the points of consumption, the electricity grid needs to be restructured and expanded. Second, as the share of renewables in the overall energy mix grows, fluctuations in the power grid will increase significantly, and new ways will have to be found to compensate for them (e.g., by flexibly adjusting the energy demand of industry and private households to the energy supply or by using batteries as storage devices) (Ragwitz et al., 2023). Third, technological solutions must be developed further and implemented in many areas that have been dominated by the use of fossil fuels for decades (e.g., the production of steel in a climate-neutral way). To address these challenges, various research initiatives have been undertaken, not least in Germany, for several years [e.g., the Kopernikus project P2X (Ausfelder and Dinh, 2022) or the Carbon2Chem project (Thonemann and Maga, 2020)].[1] For some challenges, certain solutions have already been tested and implemented. Answers to other problems are still being researched.

However, the transformation will require considerable investment, the feasibility of some solutions is controversial, and the impact on many areas of daily life is assumed to be significant. Accordingly, the energy transition is not only a technological but also a social transformation. This process is accompanied by many uncertainties regarding the necessary decisions and their consequences. Therefore, forthcoming changes can provoke people's anxiety and the rejection of the transformation. However, in a democracy, such a fundamental change needs support from society.

For a long time, science communication has assumed that support for innovative technologies can be generated by informing the public. From this perspective, overcoming people's concerns or resistance to changes would be a matter of knowledge. However, research on science communication has demonstrated that providing information and improving knowledge do not guarantee the acceptance of new technologies (Schäfer et al., 2015). In some cases, even the opposite seems to be true.

Nevertheless, from a political perspective, people must understand what changes should be implemented and the risks and opportunities attached to new technologies. Only a well-informed citizen can make sound decisions during the transformation process. According to De Silva-Schmidt (2021), a lack of knowledge hampers public discourse in at least four ways. First, without knowledge, citizens cannot participate adequately in political discourses. Second, a lack of knowledge might exclude certain segments from the political debate and, consequently, deepen segregation in society. Third, a lack of knowledge makes people more vulnerable to misinformation and fake news. Fourth, low levels of knowledge can widen the gap between experts and laypersons, making it increasingly difficult for experts to be heard in public debate. Taken together, these points suggest that if citizens lack knowledge of the (possible) solutions to achieving carbon neutrality and the transformation plans based on them, they will have difficulties making the right personal and political decisions and participating adequately in the upcoming sociopolitical transformation.

The energy transition is a complex transformation process that involves many decisions and actions that have to be taken. Some of these measures have already been implemented and are known to the public. People are aware that the construction of wind turbines and solar panels and the extension of power lines form an integral part of the energy transition (Wolling and Arlt, 2015; Epp and Bellmann, 2019). In contrast, they have less knowledge of the application of green hydrogen in various sectors (Epp and Bellmann, 2019; Arndt, 2022), and a negligible proportion have heard of terms such as "power-to-gas" (vzbv, 2020) or "sector coupling" (Arndt, 2022).

From the perspective of technology diffusion research, the gradual spread of knowledge of the existence and characteristics of innovations is a typical process associated with their dissemination. Knowledge plays a decisive role in the diffusion and acceptance of technologies. According to Rogers (2003), five phases can be distinguished for the social adoption of an innovation. In the first phase, referred to as awareness-knowledge, an individual learns about the existence of an innovation. This can be seen as a prerequisite for adopting an innovation. In the next step, knowledge of the correct application of an innovation (how-to-knowledge) and the basic knowledge of how an innovation works (principles-knowledge) can and should be acquired. The knowledge gained in this phase forms an essential basis for the subsequent persuasion phase in which individuals develop certain attitudes toward the innovation (Rogers, 2003).

Building on this, literature reviews on the acceptance of sustainable energy technologies (Huijts et al., 2012; Scovell, 2022) have revealed positive correlations between knowledge and the acceptance of these technologies. In the case of the acceptance of hydrogen energy technologies, this applies to both awareness of the existence of these technologies and objective knowledge of the properties of hydrogen and related technologies (Scovell, 2022). In the logic of Roger's model, objective knowledge is called principles-knowledge.

As different technological innovations of the energy transition belong to different phases of the diffusion process, knowledge concerning these innovations has reached different stages. Based on the aforementioned model we have to differentiate between two types of innovation: awareness-knowledge is relevant in the case of latest innovations such as power-to-X or sector coupling, while principles-knowledge becomes relevant in the case of technologies that are already under discussion for a long time such as hydrogen.

Thus, the aim of this paper is to examine the population's *level of awareness-knowledge or principles-knowledge* of different technological solutions at different stages of diffusion that could contribute to achieving carbon neutrality. Moreover, we are interested in the *relevant factors that might influence these levels of knowledge*.

In what follows, we will first scrutinize the question of what technological solutions in the context of the energy transition

1 For further information on the research projects, visit https://www.kopernikus-projekte.de/en/home and https://www.umsicht.fraunhofer.de/en/lines-of-research/carbon-cycle.html.

that citizens should know about. Here, we argue about the benefits of transdisciplinary research projects in which scientists from various disciplines jointly identify relevant knowledge for citizens. Accordingly, we will present knowledge categories on the energy transition identified in the transdisciplinary research project "Wissenschaftskommunikation Energiewende."[2]

Second, we will turn to possible sources for gaining this knowledge. As mainstream media and social media are relevant channels of information and arenas of discourse on any topic of sociopolitical relevance, we also see the media as a central driver in the level of knowledge of the energy transition. Thus, we scrutinize the role of the media and, in doing so, extend existing perspectives as follows: We particularly focus on the role of online and social media in the level of knowledge. While previous studies had only generally examined the role of the Internet (e.g., Kahlor and Rosenthal, 2009; Taddicken, 2013), we propose a more precise view on what types of sources people rely on in this highly selective online environment. This is relevant from a science communication perspective, as the results might show how important (or not) direct communication between, for example, scientists and citizens is for the knowledge acquisition process when compared to information obtained from traditional media.

We then present our data, operationalization, and analytical strategy to address our research questions. Following this, the findings are described, and the contribution of our study to the current state of research is discussed.

2. Technological solutions for the energy transition that citizens should know about

Technological solutions for the energy transition enable a complete shift to renewable energies and thus contribute significantly to achieving carbon neutrality. We argue that these technological solutions are an important part of climate research, since it aims not only to provide information on the causes, trends, and consequences of global warming but also to identify options for action and for achieving climate goals (IPCC, 2022).

A typology based on existing research (Taddicken et al., 2018) shows that the research focuses on three types of knowledge: knowledge of the causes of climate change (e.g., Cabecinhas et al., 2008; Taddicken, 2013); knowledge of its consequences (Taddicken, 2013; Oschatz et al., 2019); and action-related knowledge, mostly related to individual behaviors to reduce greenhouse gas emissions (Yang and Ho, 2017; Loy et al., 2020).

In contrast, research on the energy transition scrutinizing the knowledge of technological solutions beyond renewable energies is rare, and the few studies available have focused predominantly on hydrogen technologies (Zaunbrecher et al., 2016; Epp and Bellmann, 2019; Konrad et al., 2021; Arndt, 2022). Overall, the findings show that the level of awareness-knowledge with hydrogen and its use as a future energy carrier is relatively high. In 2006, 66% of Germans had heard about hydrogen energy and cars (European Commission, 2007). According to more recent surveys, around 80% of Germans have awareness-knowledge of hydrogen and its use (Konrad et al., 2021; Isidoro Losada, 2022). In contrast, the awareness of other important technologies to realize the energy transition, such as "power-to-gas" or "sector coupling," is rather low among Germans (vzbv, 2020; Arndt, 2022).

In summary, little is known about people's knowledge of actual technological solutions in the field of the energy transition. However, this raises the following question: what *exactly* do citizens need to know about technological solutions in terms of the energy transition? In other words, what is relevant knowledge for citizens, and how do we identify it? Due to the lack of studies in this area, we could only answer this question to a limited extent based on existing research. Accordingly, we had to develop new indicators for relevant knowledge in the field. Therefore, we combined the deduction of categories from existing studies with another, more inductive gateway.

Fortunately, we are part of the transdisciplinary research project "Wissenschaftskommunikation Energiewende." The goal of this project is to show and explain current technological developments for achieving carbon neutrality to the broader public. One important aim of the project is to generate knowledge of these solutions. For this purpose, an exhibition called "Power2Change: Mission Energiewende"[3] was jointly planned by a transdisciplinary team comprising (a) natural scientists and engineers working on technological solutions for the energy transition, (b) pedagogues and employees of museums where the exhibition will be conducted, and (c) communication scientists working in the field of political and science communication.

As a starting point, natural scientists and engineers presented their current approaches following a list of questions developed by social scientists and museums. For example, they were asked to explain the energy transition and their research project to a 12-year-old child; they were expected to indicate what is critical and positive about their project from the public's viewpoint and which areas (industry, electricity, transport, etc.) their project primarily addresses. In several workshops, main themes for the exhibition were identified, and two relevant categories of required knowledge of current technological solutions in the field of the energy transition were derived. First, citizens *need to be aware of forthcoming changes in the energy system*. In particular, the following five changes are central to this context:

- *Electrification,* meaning that the energy supply of industry, transport, and buildings is converted—as far as possible—from natural gas, oil, and coal to electricity from renewable energies to reduce CO_2 emissions from fossil fuels.
- *Decentralization of the energy supply,* meaning that electricity is not produced centrally and supra-regionally in a few large plants and power stations but locally in many small plants.
- *Flexibilization of energy demand,* meaning that industry and private households have to adapt their electricity consumption to the fluctuating supply of renewable energies.

2 The transdisciplinary research project "Wissenschaftskommunikation Energiewende" (translated: Science Communication Energy Transition) is funded by Federal Ministry of Education and Research (Nb. 03SF0625E).

3 https://power2change-energiewende.de

- *Power-to-X,* meaning that electricity (power) is used to produce gases such as hydrogen, synthetic fuels, or other substances.
- *Sector coupling,* comprising an energy system in which the transport, buildings, and industry sectors are closely interconnected and flexibly exchange energy sources of electricity, gas, and heat.

Second, the knowledge of hydrogen was identified as relevant by the interdisciplinary research group. The German government has designated hydrogen as a key element for the energy transition because it has several applications as a substitute for natural gas, oil, and coal (Bundesministerium für Wirtschaft und Energie, 2020). In particular, green hydrogen, which is produced by electrolysis using renewable energy, enables a significant reduction of CO_2 emissions in industry and transport. Its possible applications are manifold. For example, green hydrogen can be used directly as a final energy carrier in the steel industry to reduce greenhouse gas emissions from steel production. In addition, hydrogen forms the basis for producing synthetic fuels or other chemicals. Finally, it can also be used to store energy. Accordingly, *knowledge of the availability, production, and possible applications of hydrogen* was identified as the second important dimension citizens should know about.

Returning to the phases of knowledge diffusion defined by Rogers (2003), we argue that knowledge of the *forthcoming changes in the energy system* is in the phase of *awareness-knowledge.* As the few existing studies have shown, people are hardly yet aware of these changes. In contrast, the diffusion of knowledge of hydrogen should have already entered the phase of principles-knowledge, as awareness-knowledge is already high in the population (European Commission, 2007; Konrad et al., 2021; Isidoro Losada, 2022). Having identified these knowledge categories, our initial research questions are as follows:

> *RQ1: How much awareness-knowledge does the German population have concerning forthcoming changes in the energy system?*
> *RQ2: How much principles-knowledge does the German population have about hydrogen as an important tool for the energy transition?*

In addition to these descriptive questions, and as indicated earlier, we are also interested in the factors related to people's level of knowledge, which we will discuss in the next chapter.

3. Knowledge of the energy transition and the role of the media

Various theoretical approaches in communication science posit that people learn and acquire knowledge from the news and information they consume. For example, agenda-setting theory assumes that the public learns about important issues in society from the media (Wanta, 1997). By putting certain issues on the agenda, the media influences not only what issues citizens think about and consider important but also what issues they learn about. "Therefore, the messages sent via the news media impact individuals' perceptions and knowledge" (Wanta and Tarasevich, 2019). Likewise, an essential assumption of the knowledge gap hypothesis posits that people gain knowledge through the diffusion of information using mass media (Lind and Boomgaarden, 2019). Consequently, it can be presumed that the media and the information they disseminate affect people's level of knowledge.

Regarding our object of investigation, both content analyses of media coverage (e.g., Sengers et al., 2010; Stauffacher et al., 2015; Lyytimäki et al., 2018; Rochyadi-Reetz et al., 2019) and studies on social media (Rantala et al., 2020; Corbett and Savarimuthu, 2022; Vespa et al., 2022) have revealed that the energy transition is a relevant subject of mediated communication. Accordingly, it stands to reason that the media, both mass media and social media, play important roles in the dissemination of information about the energy transition and related technological solutions, thus enabling people to acquire related knowledge.

In contrast, significantly fewer studies have dealt with the reception of media content about the energy transition and its possible connections with knowledge. A recent study showed that around three-fifths of Germans regularly or at least occasionally use the media to inform themselves about the energy transition (Arndt, 2022). Likewise, Schumann et al. (2015) found that Germans use television, internet, and newspapers to inform themselves about grid expansion. Concerning the relation between media use and knowledge, Wolling and Arlt (2015) found that more intense energy-related information usage is related to higher levels of knowledge of different aspects of the German energy transition.

Only a few studies have examined the role of the media in people's knowledge of the energy transition as an important solution to addressing climate change. Nevertheless, a few conclusions can be drawn from studies examining the relation between media use and other aspects of climate change-related knowledge. However, these studies used other classification systems, as proposed in the introduction. As we conducted research on the knowledge of innovative technologies, we referred to a model that is used for investigating technology dissemination. Such a model is hardly applicable to the knowledge of climate change. Instead, these studies frequently distinguished between objective knowledge (e.g., Cabecinhas et al., 2008; Taddicken, 2013; Ho and Yang, 2018; De Silva-Schmidt et al., 2022) and subjective knowledge (Zhao, 2009), also called perceived knowledge (Ho et al., 2014). The objective approach characterizes knowledge as either right or wrong, while subjective knowledge refers to people's subjective assessment of their own level of knowledge in the sense of awareness-knowledge (Rogers, 2003). Furthermore, they also included other indicators, such as behavioral knowledge.

Within this research field, scholars have applied different measurements of media use, ranging from rather broad indicators to the analysis of certain specific media types that recipients use to inform themselves about climate change. Using global media use indicators, several scholars have found that both attention to climate messages in various media sources and attention especially to climate news in traditional media are positively related to knowledge of climate change (Ho et al., 2014; Yang and Ho, 2017; Ho and Yang, 2018; Loy et al., 2020).

Regarding the use of television, various studies have found no or very limited effects (Kahlor and Rosenthal, 2009; Zhao, 2009; Taddicken, 2013; Yang and Ho, 2017; Oschatz et al., 2019). When distinguishing between public and commercial television, Cabecinhas et al. (2008) found that knowledge of climate change was higher among those using public television than among those using commercial television. In De Silva-Schmidt et al.'s (2022) study, exposure to commercial television was negatively associated with knowledge of climate policy.

Similarly, mixed findings have been obtained for newspaper use. Some scholars have found positive relations between topic-specific use of newspapers and knowledge of climate change (Stamm et al., 2000; Yang and Ho, 2017; Oschatz et al., 2019), while others could not confirm such a relation (Taddicken, 2013). Looking more closely at the different types of newspapers, De Silva-Schmidt et al. (2022) found a positive effect of reading regional print newspapers on knowledge of climate policy but not on reading national print media, weekly newspapers and magazines, and the leading German tabloid BILD.

Besides traditional media researchers also investigated the role of online media in people's knowledge of climate change. Here again, diverse findings were obtained, showing both positive (Zhao, 2009) and no associations (Kahlor and Rosenthal, 2009; Taddicken, 2013). Similarly, several studies have found no associations between topic-specific use of online media and knowledge of climate change (Taddicken, 2013; Ho and Yang, 2018; Oschatz et al., 2019). Only De Silva-Schmidt et al. (2022) reported a positive effect of using a specific quality news website on knowledge of climate policy.

In summary, the findings presented show that the state of research to date is fragmented and does not provide a clear picture of the relations between media use and climate-related knowledge. Additionally, the variety of indicators applied to the media makes it difficult to draw general conclusions, especially to formulate concrete hypotheses. Furthermore, the studies were conducted in different countries with different media systems and media use patterns. This can also explain the variance in the findings. Nevertheless, a certain degree of differentiation in measuring media use seems essential to gain meaningful insights into the connections between media use and knowledge. For example, the results indicate that the uses of public and private television have different effects on the level of knowledge (Cabecinhas et al., 2008; De Silva-Schmidt et al., 2022).

However, while some differentiations have been made concerning traditional media, this is hardly the case in terms of the effects of using "the internet" (e.g., Kahlor and Rosenthal, 2009; Zhao, 2009; Taddicken, 2013). This could also be one reason why hardly any effects of online media have been identified so far. Given the rather selective nature of online use—especially of social media—it makes little sense to ask about the general use of online media; rather, we should have a closer look at the specific sources and actors from which people receive information using online media. In particular, social media have become an important communication channel that allows actors to disseminate information directly to the public (e.g., scientists; Brossard and Scheufele, 2013). In addition, in the context of the energy transition, actors from the political, scientific, or economic sphere directly provide relevant information through social media, blogs, or their own websites. Accordingly, it is relevant to consider whether a recipient's exposure to these direct forms of communication varies in its association with the level of knowledge. To the best of our knowledge, there have been no studies on this so far, and we want to expand the existing state of research in this regard.

Given the considerations outlined above, we draw the following conclusions for examining the relation between media use and knowledge of technological solutions in the context of the energy transition. Fundamentally, we differentiate between two forms of sources from which people receive information concerning the energy transition. This is, on the one hand, traditional journalistic media, such as television or newspapers, whereby we do not further differentiate between whether the information is received online or offline. On the other hand, we look at different actors as sources that directly provide information on the energy transition mainly through various online channels, such as social media, blogs, or websites. This leads to our third and fourth research questions:[4]

> *RQ3: How does the usage of information on the energy transition from different journalistic media and from different actors through online media relate to the level of awareness-knowledge concerning the forthcoming changes in the energy system?*
>
> *RQ4: How does the usage of information on the energy transition from different journalistic media and from different actors through online media relate to the level of principles-knowledge of hydrogen as an important tool for the energy transition?*

In addition to the previously mentioned factors, there are several other elements that can affect people's levels of knowledge. In the context of climate knowledge, previous research has shown that, besides formal education (Tobler et al., 2012; De Silva-Schmidt et al., 2022), motivational factors, such as issue importance (De Silva-Schmidt et al., 2022); issue-related attitudes, namely climate skepticism (Hart et al., 2015); and interpersonal discussions (Stamm et al., 2000) are also related to people's level of knowledge. Hence, we will consider them as controls in our study.

Finally, our assumed relations between media use and people's level of knowledge (RQ3–RQ4) can be summarized in a research model that serves as the basis for our data analysis (Figure 1).

4. Methods

4.1. Sample

This study used data from a nationwide online survey ($N = 2{,}025$), which was conducted with a commercial online access panel (ISO-certified, 20252:2019) from August 19 to August 30, 2021. The sampling was based on a quota selection stratified by the gender, age, and education of German-speaking online users between the ages of 14 and 65 residing in the territory of Germany.

4 We are aware that we cannot prove any causal effects of media use and the level of knowledge on the basis of cross-sectional data. Nevertheless, with reference to the state of research and the indicators considered here for the media variables and knowledge, it seems more plausible to us to assume effects of the more general media variables (related to the energy transition) on specific knowledge (knowledge about technological solutions in the context of energy transition) than vice versa.

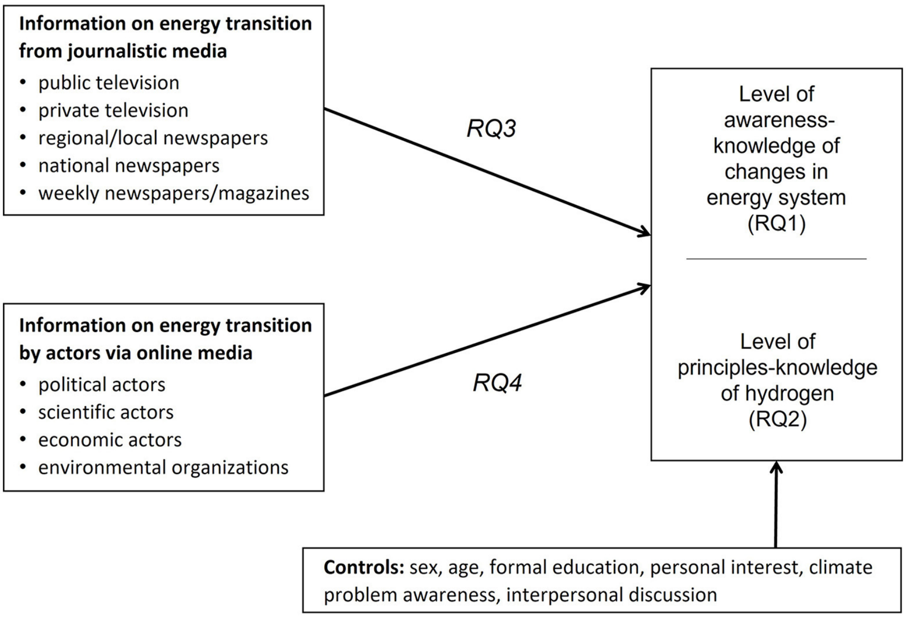

FIGURE 1
Research model.

The average age of the respondents was 42 years (SD = 14.21). Of the participants, 50% were women and 50% were men. In terms of their education level, 30% had basic formal education, 33% had intermediate education, and 37% had higher education. The average monthly household net income was 2,500 euros.

4.2. Measurements

4.2.1. Awareness-knowledge of changes in the energy system

For awareness-knowledge, we asked the participants about their awareness (e.g., Konrad et al., 2021; Arndt, 2022; Isidoro Losada, 2022) regarding the five fundamental changes in the energy system identified within our transdisciplinary project (flexibilization, sector coupling, power-to-X, decentralization, and electrification). To prevent the participants from reporting the right knowledge inadvertently, we added a brief explanation of each topic. Accordingly, the respondents could better assess whether they really had heard about the respective transformation and accordingly had awareness-knowledge. For each technological change, the participants were asked to state whether they had heard of these changes before and whether they had an idea of what they meant (for further details see Table 2 in chapter 5). The answer category "Yes, I had heard about it and knew what it meant beforehand" was considered awareness-knowledge, while the other two ("No, I had never heard of it until just now" and "Yes, I had heard of it, but I didn't know what it meant") characterized a lack of knowledge. For further analyses, a sum index was formed by building a scale on the changes in energy systems ranging from no knowledge (0 = no awareness of none of the 5 changes) to high knowledge (5 = awareness of all 5 changes).

4.2.2. Principles-knowledge of hydrogen

We used true-false questions to measure people's principles-knowledge of the availability, production, and possible applications of hydrogen (for further details see Table 3 in chapter 5). For the five statements, the respondents were asked to indicate whether they were true or false; they also had the option to answer "don't know." Consequently, each item could be answered correctly, incorrectly, or as "don't know." In contrast to a dichotomous response format (true vs. false), this format has the advantage of reducing the guessing problem (Sturgis et al., 2008) and enabling a distinction among correct, false, and missing knowledge (Taddicken et al., 2018). Regarding index formation, we followed the argumentation of Taddicken et al. (2018) and formed a sum index of correct knowledge (+1), false knowledge (−1), and missing knowledge (0); to the best of our knowledge, such a system has not yet been implemented empirically. Theoretically, this index can take values between −5 (all answers are wrong) and +5 (all answers are right).[5]

4.2.3. Use of information on the energy transition from journalistic media and non-media actors online

In this study, a distinction was made between two basic communication channels for obtaining information on the energy

5 The knowledge scales constructed for the survey do not consist of items that are in principle interchangeable. Instead, the items complement each other by addressing different aspects of the respective knowledge. Accordingly the indicators together adequately measure the underlying construct, but the individual indicators are not necessarily highly correlated. This assumption is confirmed by the low alpha values (awareness knowledge—alpha = 0.76; principle knowledge—alpha = 0.43).

transition. On the one hand, we measured how frequently people receive information on the energy transition through different journalistic media (public television, private television, regional/local newspapers, national newspapers, and weekly newspapers/magazines), no matter whether online or offline. On the other hand, we assessed how frequently people receive information on the energy transition from non-media actors and organizations (political actors, economic actors, environmental organizations, and scientific actors) that directly communicate through social media, blogs, or websites. The respondents were asked to indicate on a 7-point scale (0 = never; 6 = daily) how often they had received information on the energy transition from all these media and actors in the past months. As shown in Table 1, public television was the most important information source for the energy transition, followed by non-media actors. In the context of the energy transition, for many people, the direct communication of political actors or environmental organizations played an even more important role than national or weekly newspapers and magazines.

4.2.4. Controls

In addition to age, education, and gender, four other variables were measured as controls: *Personal interest* was determined on a 5-point scale (1 = no interest at all; 5 = very strong interest), with four items (interest in energy and climate policy, $M = 3.3$, SD = 1.1; research on climate protection, $M = 3.2$, SD = 1.1; technological developments in the field of renewable energies, $M = 3.2$, SD = 1.1; technical developments on the use of hydrogen, $M = 3.1$, SD = 1.2). For all further analyses, an index of issue-related interest ($M = 3.2$, SD = 1.0, $\alpha = 0.91$) was formed. *Attitudes toward climate change* was measured with five items ["Human activities are the main cause of current climate change," "It is not at all certain that climate change actually exists (reversed)," "Climate change is not as dangerous as we are led to believe (reversed)," "The many extreme weather events clearly show that climate change is happening," "Climate change is one of the greatest threats to humanity"] on a 5-point scale (1 = strongly disagree; 5 = strongly agree) and summarized into a mean index ($M = 3.9$, SD = 1.0, $\alpha = 0.88$). The higher the mean, the greater the respondents' awareness of climate problems. To measure *interpersonal discussion about the energy transition*, the participants were asked the following two questions: (a) how often do you talk about the energy transition with family or friends and (b) how often do you talk with colleagues and acquaintances. The answers to both items were measured on a 7-point scale (0 = never; 6 = daily; $M = 3.2$, SD = 1.0, $r = 0.72$).

4.2.5. Analytical strategy

To answer our first two research questions concerning awareness-knowledge of fundamental changes in the energy system (RQ1) and principles-knowledge of the availability, production, and possible applications of hydrogen (RQ2), we calculated frequencies to reveal the distribution of the answers. To address our research questions (RQ3 and RQ4), we applied blockwise regression analysis. In the first step, we introduced all control variables to avoid obtaining random results. In the second step, we tested the effects of receiving information from journalistic media and, in the third step, those of receiving information from different non-media actors. However, due to high correlations between newspapers and magazine usage, on the one hand,[6] and the uses of information from different non-media actors through social media, blogs, websites, or podcasts, on the other hand,[7] we could not test all of them together because this caused a problem with multicollinearity. One way to avoid multicollinearity would have been to combine the variables into an index. However, this would have contradicted our previous argument that it is important to look at the effects as precisely as possible and to differentiate more strongly in online media. Accordingly, the variables were tested in separate models. Finally, we tested our models at a significance level of 1% and below to avoid erroneous recognition of significance.

5. Results

Concerning awareness-knowledge of the upcoming changes in the energy system (RQ1), the findings in Table 2 reveal significant differences. The best-known aspect was the transformation of the energy supply system of industry, transport, and buildings into electricity from renewable energies, also known as *electrification*. According to their assessment, four out of ten respondents knew what this meant. However, in the case of the decentralization of the energy supply, not even one-third claimed to understand the concept. Regarding the use of power-to-X technologies or planned sector coupling, not even one in seven knew what it meant. Around two-thirds of the participants had never even heard of these two concepts at the time of the survey. Overall, it can be said that the majority of the population has limited knowledge of imminent changes in the energy system. As the findings based on the sum index show, half of the population (50%) has no knowledge of any of these changes, 18% knows about one of the changes; and only 4% have knowledge of all five changes. On average, one change is known (M = 1.2, SD = 1.4, MIN = 0, MAX = 5).

Likewise, the principles-knowledge of hydrogen is rather low (RQ2). The fact that hydrogen in its pure form is virtually non-existent in nature was correctly noted by about one-third of the respondents (Table 3). About one-quarter mistakenly thought that this statement was incorrect, and four out of ten said they did not know. A similar pattern was observed for the statement that little energy is required to produce hydrogen. A somewhat higher level of knowledge was observed in the answers to the other three statements. In particular, slightly more than half knew that hydrogen production is still very expensive, and slightly less than half knew that hydrogen can be produced using electric power.

6 Regional/local newspapers with national newspapers: $r = 0.66$, $p < 0.001$; national newspapers with weekly newspapers/magazines: $r = 0.72$, $p < 0.001$; regional/local newspapers with weekly newspapers/magazines: $r = 0.61$, $p < 0.001$.

7 Political actors with economic actors: $r = 0.83$, $p < 0.001$; political actors with environmental organizations: $r = 0.77$, $p < 0.001$; political actors with scientific actors: $r = 0.75$, $p < 0.001$; environmental organizations with scientific actors: $r = 0.80$, $p < 0.001$; environmental organizations with economic actors: $r = 0.75$, $p < 0.001$; scientific actors with economic actors $r = 0.74$, $p < 0.001$.

TABLE 1 The usage of information on energy transition.

	M (SD)[a]	At least once a week[b]	Less frequently[c]	Never
Information on energy transition from journalistic media (including their online presence)				
Public television	2.6 (2.1)	36%	40%	24%
Private television	2.3 (2.0)	29%	44%	28%
Regional/local newspapers	2.3 (2.0)	29%	42%	29%
National newspapers	1.9 (1.9)	24%	40%	36%
Weekly newspapers/magazines	1.8 (1.8)	21%	42%	37%
By actors through social media, blogs, websites, or podcasts				
Political actors	2.1 (1.9)	25%	42%	34%
Environmental organizations	2.0 (1.9)	24%	41%	36%
Scientific actors	1.7 (1.8)	18%	43%	39%
Economic actors	1.5 (1.6)	13%	44%	43%

[a]Mean values (M) and standard deviations (SD) on a 7-point scale (6 = daily, 5 = several times a week, 4 = once a week, 3 = several times a month, 2 = about once a month, 1 = less than once a month, 0 = never).
[b]At least once a week (scale points 6–4).
[c]Less frequently (scale points 3–1).

TABLE 2 Awareness-knowledge of changes in the energy system.

	Lack of knowledge		Knowledge
	No, I had never heard of it until just now	Yes, I had heard of it, but I didn't know what it meant	Yes, I had heard about it and knew what it meant beforehand
Electrification: the energy supply of industry, transport, and buildings is converted—as far as possible—from natural gas, oil, and coal to electricity from renewable energies to reduce CO_2 emissions from fossil fuels	31%	30%	38%
Decentralization of the energy supply: electricity is not produced centrally and supra-regionally in a few large plants and power stations but locally in many small plants	45%	26%	29%
Flexibilization of the energy demand: as the supply of renewable energies fluctuates, industry, and private households need to adapt their electricity consumption to the current supply	53%	27%	20%
Power-to-X: electricity (power) is used to produce gases such as hydrogen, synthetic fuels, or other substances	65%	21%	14%
Sector coupling: the future energy system is based on the point that transport, buildings, and industry are closely interconnected and that the energy sources of electricity, gas, and heat can be flexibly exchanged among these areas	66%	22%	12%
Question: Many changes in energy supply are planned as part of energy transition. Had you heard of the following changes before this survey, and do you know what these terms mean?			

N = 2,025.

Regarding the application of hydrogen, slightly more than half knew that synthetic fuels could be produced from hydrogen.

The sum index showed, that the respondents gave slightly more than one correct answer on average (MIN = −5, MAX = 5, M = 1.4, SD = 1.9). Ten percent showed a very high level of knowledge, answering all statements correctly. Even more impressive, however, was the finding that the proportion of those who said they did not know the answer was between 35 and 45% for all statements. This clearly illustrates the relevance of the "not knowing" category and the distinction between those who answered the statements incorrectly. This share varied between 8 and 26%, depending on the statement. The two categories of knowledge (awareness and principles) were found to be positively related at a low level ($r = 0.29$, $p < 0.001$).

Table 4 presents the results of the regression analysis. It shows the associations between the use of information on the energy transition from journalistic media and non-media actors with awareness-knowledge and principles-knowledge (RQ3 and RQ4). The results of the regression analyses on the two knowledge indicators have many commonalities as well as some striking differences. The description of the results is comparative, highlighting these similarities and discrepancies. First, the existing variance in both dependent variables can only be explained to a

TABLE 3 Principles-knowledge of hydrogen.

	Answer given by respondents:	True	False	Don't know
Availability	Pure hydrogen is almost infinite in nature. (False)	26%	34%	40%
Extraction	Only a little energy is required to produce hydrogen. (False)	22%	37%	41%
Extraction	The production of hydrogen with electric energy is still very expensive. (True)	52%	8%	40%
Extraction	Hydrogen can be obtained from water using electric energy. (True)	45%	10%	45%
Application	Hydrogen can be used to produce synthetic fuels for cars, trucks, ships, and aircraft. (True)	52%	13%	35%
Question: Which of the following statements about hydrogen do you think are true and which are false?				

N = 2,025.

TABLE 4 Regression analysis for both knowledge categories.

	Awareness-knowledge of changes in energy system			Principles-knowledge of hydrogen			
	M1	M2	M3	M1	M2	M3a	M3b
N	2,011	1,863	1,753	1,885	1,784	1,784	1,751
Corr. R^2	0.21	0.22	0.22	0.11	0.11	0.11	0.11
β-coefficients							
Controls							
Sex (male)	0.13***	0.13***	0.13***	0.23***	0.23***	0.22***	0.22***
Age (in years)							
Formal education (high)	0.12***	0.12***	0.11***	0.11***	0.11***	0.11***	0.11***
Personal interest (strong)	0.26***	0.25***	0.22***	0.10***	0.11***	0.12***	0.12***
Climate problem awareness (high)				0.11***	0.10***	0.11***	0.11***
Interpersonal discussion (frequent)	0.16***	0.17***	0.15***				
Information on energy transition from journalistic media (frequency)							
Public television		0.09**	0.08**				
Private television		−0.11***	−0.12***		−0.06**		
Regional/local newspapers							
National newspapers							
Newspapers/magazines[a]							
Information on energy transition by actors through social media, blogs, websites, or podcasts (frequency)[b]							
Scientific actors			0.10***				
Political actors						−0.08**	
Economic actors							−0.07**
Environmental organizations							

***$p < 0.001$.
**$p < 0.01$.
[a]Because of multicollinearity problems, we tested the effects of receiving information from (a) regional/local newspapers, (b) national newspapers, and (c) weekly newspapers/magazines in separate regression models. None of the models showed significant effects.
[b]For the same reason, the effects of receiving information from different actors (political actors, economic actors, environmental organizations, and scientific actors) were also tested individually. However, effects were found only in three cases.

relatively small extent. For principles-knowledge of hydrogen it is about 10%, and for awareness knowledge, the explained variance is about 20%. The inclusion of the media variable does not contribute in any significant way in improving the explained variance of the models.

The second striking commonality was the remarkable relation between the control variables and the level of knowledge for both categories. These relations remained quite stable after the media exposure variables were introduced. In the final models (see columns M3, M3a, and M3b in Table 4), sex, formal education, and personal interest were positively related to the level of knowledge, while age was unrelated. The effect of education was similar on both knowledge categories ($\beta = 0.11$). Furthermore, in both models, male participants had higher levels of knowledge than females. This effect was somewhat stronger for principles-knowledge of hydrogen ($\beta = 0.22$). In contrast, the effect of personal interest was somewhat stronger on awareness-knowledge of changes in the energy system ($\beta = 0.22$) than on principles-knowledge of hydrogen ($\beta = 0.12$).

Differences between the two models appeared regarding climate problem awareness and interpersonal discussions. While climate problem awareness was positively related to principles-knowledge of hydrogen, there was no relation with awareness-knowledge of changes in the energy system. In contrast, awareness-knowledge was related to the intensity of interpersonal communication on the energy transition, whereas the level of principles-knowledge of hydrogen remained unaffected.

In addition to the similarity in the effects of the control variables, the second important common feature was that hardly any correlations were observed in the reception of information from different media sources. In particular, the use of newspapers and magazines was not associated with the level of knowledge in any of the models. Some differences occurred concerning the other indicators for receiving information on the energy transition. In contrast, there were different relations between the usage of public and private television. Concerning awareness-knowledge of changes in the energy system, the results revealed that persons who relied on public television to obtain information on the energy transition reported more frequently that they were aware of these changes in the energy system ($\beta = 0.08$), while the opposite effect occurred for those who relied on private television ($\beta = -0.12$). In contrast, in the final models for principles-knowledge of hydrogen (M3a and M3b), neither private nor public television showed any significant effect. On the other hand, we observed certain small effects of information provided by some of the non-media actors. We identified a positive relation between receiving information from scientific actors and awareness-knowledge of changes in energy supply but a negative relation between information provided by political and economic actors on the principles-knowledge of hydrogen. Those who receive more information from these actors about the energy transition know less about the principles of hydrogen use.

6. Discussion and future research directions

In our paper, we focused on citizen's knowledge of *technological solutions for realizing the energy transition*. We argue that a lack of knowledge can hinder their participation in the upcoming transformation process. The question of which technological solutions citizens should be knowledgeable about was developed as part of a transdisciplinary research project in collaboration with natural scientists and engineering scientists who are currently working on and researching such solutions. Two categories were identified: (a) awareness-knowledge of fundamental changes in the energy supply system and (b) principles-knowledge of the availability, production, and possible applications of hydrogen.

Based on a representative survey, we first analyzed the level of knowledge in these two knowledge categories among the German population (RQ1 and RQ2). Overall, our study revealed notable knowledge deficits in both cases. Although previous research has shown that the German population has awareness-knowledge of hydrogen (European Commission, 2007; Konrad et al., 2021; Isidoro Losada, 2022), the level of principles-knowledge remains low. However, as hydrogen is often discussed as *the* solution for the future of energy supply and has been declared a key element of the energy transition, we assessed the relatively low levels of principles-knowledge of hydrogen as problematic. Moreover, we found that changes in the energy system and corresponding future technologies, such as power-to-X or sector coupling, are still widely unknown in the population. These results are in line with those obtained by other studies that have shown "power-to-gas" or "sector coupling" to be widely unknown to the great majority of Germans (vzbv, 2020; Arndt, 2022, p. 22).

Coming back to the relevance of knowledge of technological solutions for citizens' opinion making on the feasibility of the transformation and their participation in transformation processes, we see a great need to increase such knowledge in society. This is important, especially because the construction of large-scale plants for the production of hydrogen, the construction of pipelines for transport, the question of imports to Germany, and the discussion of whether e-fuels can be an alternative to e-mobility will be topics of controversial public and political discourses in the coming years.

However, what influences the level of knowledge and what role does the media play in this context? We addressed these questions with our research questions RQ3 and RQ4. Our main emphasis was on the role of the media in the level of knowledge. Based on existing studies in the field of climate change, we first focused on the role of traditional media use. Furthermore, we extended this approach and scrutinized the impact of non-media actors communicating directly with the public on social or other online media. In addition, we controlled for sociodemographic and other individual variables, such as personal interests or relevant attitudes.

For both knowledge categories, our findings revealed stable patterns of influences from the control variables. Those who had the highest awareness-knowledge and principles-knowledge were typically male, highly formally educated, and people with a high personal interest in climate change. These findings once again demonstrate the unequal distribution of knowledge in different segments of society. In addition, climate problem awareness and interpersonal discussion also play a role. Interpersonal communication seems to be important, especially in the initial phase of creating awareness, while a deeper understanding of the proposed solutions (principles-knowledge) is mainly held by those who understand the seriousness of the climate problem. All these findings illustrate how much the creation of knowledge depends on the individual characteristics of people. Especially those who understand the actual dangerousness of the underlying problem that requires these technological solutions acquire a deeper principles-knowledge. Such knowledge is required if people are to actively participate in the political decision-making process as informed citizens. In the case of awareness-knowledge, on the other hand, it is not risk perception but primarily interest in the topic that significantly influences whether people are aware of possible solutions to the climate crisis. For this "initial" knowledge-stage, climate consciousness does not play a role.

Turning to the media variables, we will discuss them from the perspective of an independent variable that impacts the knowledge categories. We are aware that our statistical analysis with regressions does not allow us to deduce causality. However, theoretically speaking, the direction of the effects is rather plausible: obtaining information from the media should proceed with the knowledge among the population. Despite the statistical limitations, we therefore decided to consider media exposure as a prerequisite that impacts the knowledge. However, we found only limited and rather fragmented influence on the level of knowledge for both categories. This is in line with the results obtained by previous studies on climate knowledge (e.g., Stamm et al., 2000; Taddicken, 2013; Oschatz et al., 2019; De Silva-Schmidt et al., 2022). Furthermore, the media variables hardly increased the explained variance in the models. Moreover, our results indicated stronger *negative* than positive associations. While the usage of public TV had slight positive associations with awareness-knowledge, exposure to private television showed negative associations with awareness-knowledge of important changes in the energy system. One possible explanation could be that private broadcasting has been repeatedly criticized for its omnipresent focus on tabloidization, disregarding important political topics, lack of background information, and negativism (for an overview, see Schuck, 2017). Apparently, this way of selecting and presenting news also hampers even the recipients' basic knowledge acquisition. However, to gain more insights here, content analyses of the scope, quality, and accuracy of the respective information conveyed by the media, as well as a discussion of the findings with scientists from the field of engineering, are required.

Focusing on the role of direct communication of non-media actors with the public through online media, we found differences depending on the actor: exposure to information from scientific actors slightly raised awareness-knowledge on the changes in the energy system. Even if the effect is small, we still take this result as an indication that direct communication between scientists and common people is beneficial, and thus, investing time in this can be a worthwhile endeavor in a scientist's schedule. However, considering the principles-knowledge of hydrogen, following scientists had no effect. In addition, receiving information from politicians or economic actors lowers knowledge levels. Interpretations of these findings remain highly speculative. Again, we see the need to analyze exactly what is communicated by the respective actors with content analysis. Perhaps the communication provided by these actors is somewhat inaccurate, confusing, or generally lacks clarity. Moreover, our refined measurements could still be too broad, since both groups—the economic and political actors—consist of a large number of individuals and organizations that may disseminate contradictory and, in some cases, (even intentionally) false information about the energy transition.

Thus, we can conclude that media play just a marginal role in the awareness-knowledge and principles-knowledge of technological solutions of the energy transition: neither exposure to traditional media nor direct communication between various actors and citizens showed a remarkable impact. In addition, our extended media consideration did not lead to substantial improvements.

Taken together, this brings us to reflect on a rather fundamental question: what is the importance of the media in increasing the level of people's knowledge? As stated earlier, important theories of communication research, such as agenda setting or the knowledge gap hypothesis, underline the importance of the media for knowledge acquisition. Nevertheless, empirical findings from surveys, such as ours, raise doubts about the relevance of the media. This needs insofar reflection, as the function of the media in a democracy is to provide all relevant information about sociopolitical issues that the populace needs to make informed decisions. While our data do not tell us anything about how the media provide this information, we can conclude that the population does not learn much, or even learns incorrect facts, from the media. As such, problems related to a lack of knowledge, such as vulnerability to misinformation, segregation between segments of society and/or between laypersons and experts, might be a consequence. We therefore argue that, for the success of the energy transition, the knowledge levels in society need to be improved. One could argue that the low influence of the media on knowledge levels is due to the fact that these solutions have so far been reported only occasionally, but our results do not provide any evidence that this relationship could change if reporting becomes more intensive. However, if the media hardly succeed in raising knowledge among the people, what instead are the relevant communication channels and formats to transport necessary knowledge of fundamental transitions to citizens?

Science communication has shifted its focus from a public understanding of the science approach to public engagement with science (Weingart et al., 2021). With formats of dialogue and participation, citizens should become emotionally attached, more trusting, and generally more engaged with scientific topics (Stilgoe et al., 2014; Engels, 2023). This approach does *not explicitly* emphasize knowledge transfer. However, we argue that science communication should study the potential of more dialogic sources than mass media when asking how the populace could gain knowledge in transformation processes. The positive effect of interpersonal communication on awareness-knowledge, as shown in our study, supports this idea. Perhaps the aforementioned exhibition "Power2Change" as part of our transdisciplinary research project can be such an example. However, whether the visit to such an exhibition really raises knowledge of the energy transition is not yet clear. This question can only be answered with an integrated evaluation of what visitors to the exhibition know (more) after their visit. Future studies could therefore focus on the evaluation of such formats and systematically compare their impact with the role of media exposure.

Possibly, however, the problem is even more profound. The research conducted here assumes that knowledge can be influenced by the provision of information. In fact, the present results show that personal characteristics primarily influence the level of knowledge. It is apparently not so much the availability or the quality of the information supplied that influences knowledge but much more the cognitive abilities and, above all, the motivation of people to deal with the information provided.

The question then is how to motivate people to engage with scientific information who are hardly interested in such topics and, in many cases, are overwhelmed with these topics. One conceivable approach is to impart knowledge in a playful way (Hoppe, 2016), but it would also be possible to embed such information in entertainment offerings. An example of this in the context of climate change is the film *The Day After Tomorrow* by Roland Emmerich, which spread the insight that extreme weather events can be the result of climate change. In this way, people who are not interested in traditional offers of scientific information transfer can also be reached.

Finally, our study has some limitations. Regarding knowledge of technological solutions for achieving carbon neutrality in the context of the energy transition, we distinguished between awareness-knowledge regarding upcoming changes in the energy system and principles-knowledge of hydrogen. Note that the first indicator cannot say much about the knowledge that people really have about the changes in the energy system, because we have to rely on the self-assessment of the participants. However, it does not make sense to measure principles-knowledge, for example, in the cases of power-to-X and sector coupling, where even self-reported awareness-knowledge is very low. The situation is somewhat different in the case of hydrogen. In measuring the principles-knowledge of hydrogen, three important aspects were singled out in relation to the availability, production, and possible applications of hydrogen. Although we relied on the expertise of technical experts in the field to identify these aspects, there is no guarantee that they are actually the most relevant aspects in the emerging public debate on the use of hydrogen in Germany. A further limitation of the study is its cross-sectional design. Thus, we measured a snapshot of the level of knowledge of the energy transition in the population. However, as the debate and the state of scientific knowledge are constantly changing, a longitudinal design is required to investigate changes in knowledge and the role of the media.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study involving human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

DA primarily carried out the empirical part of the paper. All authors contributed equally to writing the other parts of the manuscript.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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