International Journal of Hydrogen Energy 97 (2025) 328–337

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Stability, change, formation: Insights into the media's role in shaping attitudes toward green hydrogen in Germany

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ARTICLE INFO

Handling Editor: Ramazan Solmaz

Keywords:
Green hydrogen
Media coverage
Content analysis
Attitudes
Survey
Germany

ABSTRACT

This study uses a multi-method design to investigate the media's role in shaping Germans' attitudes toward green hydrogen. It combines an automatized content analysis of 7649 German newspaper articles published between July 2021 and June 2024 and a three-wave panel survey of the German population conducted between June 2023 and June 2024 with an initial sample of 2701 participants. The findings show that the intensity of media reporting on hydrogen was low compared to other energy-related topics. Nevertheless, participants' assessments of relative topic presence are rather accurate (rho: 0.50–0.80). A considerable number of participants were unable to position themselves toward the potential and challenges of hydrogen (23%–35%). Overall, the results indicate that media and communication tend to stabilize or change existing attitudes rather than contribute to the formation or loss of attitudes, leading to implications for the communication of relevant stakeholders.

Abbreviations

FAZ	Frankfurter Allgemeine Zeitung (German newspaper)
M	Arithmetic mean
n	Sample size
NHS	National Hydrogen Strategy
ns	not signficant
p	statistical significance
r	Pearson correlation coefficient
RQ	Research question
SD	Standard deviation
SZ	Süddeutsche Zeitung (German newspaper)
t_1	first survey wave
t_2	second survey wave
t_3	third survey wave
Greek Symbols	
α	Internal consistency (Cronbach's alpha)

1. Introduction

Increased production and usage of green hydrogen is a key element for achieving climate protection targets. Several countries, including Germany, have proposed and implemented national hydrogen strategies and roadmaps [1]. Through its National Hydrogen Strategy [NHS], Germany sets some ambitious objectives for green hydrogen to become a key element of the German energy transition. These include the development of a national hydrogen market, the creation of a regulatory framework for building the necessary transport and distribution infrastructure, and strengthening the competitiveness of German companies working in the field [2].

To promote the implementation of the NHS, the German government is funding a large number of hydrogen projects. In 2022 alone, there were more than 60 [3]. In addition, there are also many regional initiatives and networks organized as clusters, energy agencies, innovation centers, networks, associations, and organizations [4].

Despite these political aspirations and initiatives, the current processes and strategies pushing hydrogen must also be viewed critically. One problem is related to the production process, because only green hydrogen produced using renewable energies decisively contributes to climate protection [2]. However, many of the above-mentioned projects are about transportation, storage, or use of hydrogen in general, regardless of whether it is green or not.

Some scientists are also questioning the fundamental usefulness and technical feasibility of hydrogen strategies. On the one hand, these strategies merely represent a continuation of the exploitation of the Global South [5]. On the other hand, considerable technical problems remain, and existing solutions lack scalability [6]. In addition, the implementation costs are so high that they could even be counterproductive for global decarbonization efforts [7]. Some analyses show that

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https://doi.org/10.1016/j.ijhydene.2024.11.380
Received 10 September 2024; Received in revised form 20 November 2024; Accepted 21 November 2024
Available online 30 November 2024

economic efficiency can only be achieved if hydrogen can be produced from various primary energy sources, including natural gas [1], which seems quite far removed from the original objectives of the NHS. However, other analyses show green hydrogen plants to be a promising business model [8].

Taken together, the production, transportation, storage, and use of hydrogen has been the subject of intensive scientific research, legal regulations, and political controversies for years now. However, it is not clear to what extent these scientific, economical, technical, and political debates have reached the public. This question is of great interest, because how hydrogen is discussed in the media and how the population perceives this coverage and builds their attitudes toward green hydrogen can have a considerable influence on whether hydrogen technologies and infrastructures can be implemented successfully. The decision to develop extensive infrastructure for the production, storage, and transportation of hydrogen is primarily influenced by policymakers. In the decision-making process, these officials consider not only the outcomes of scientific research and the interests of economic stakeholders but also public opinion and media discourse.

According to the Influence of Presumed Media Influence approach [9], media coverage is particularly important as many politicians presume that the media has strong influence on shaping public opinion and political processes [10,11]. In turn, public opinion regarding key political issues, particularly those related to energy security, pricing, and environmental sustainability, can become crucial for citizens' voting behaviors. Accordingly, politicians are particularly attuned to media coverage surrounding energy issues and the prevailing attitudes of the public. If the media and a substantial portion of the populace express skepticism toward hydrogen technologies, this skepticism could adversely affect the swift implementation of hydrogen strategies. Similarly to protests against the expansion of wind power, the electricity grid, or the heating transition, public protests against the expansion of hydrogen seem conceivable in Germany. Consequently, such a potentially conflict-laden climate of public opinion could prevent policymakers from strongly supporting hydrogen initiatives, thereby hindering progress in this sector.

Against this background, the aim of this paper is to provide first empirical insights into this issue. Therefore, this paper is structured as follows. We first review the existing literature concerning public knowledge and attitudes toward hydrogen and media coverage on hydrogen. Based on this, we specify our research questions and state our hypotheses. Finally, we present our empirical results on the intensity of media coverage on hydrogen, the public perception of media coverage, and people's attitudes toward green hydrogen. A particular focus is on the media's role in the opinion-forming process.

2. State of social science research on hydrogen

2.1. Hydrogen from the population's perspective: awareness, knowledge, and opinion

The population's perspective on hydrogen technologies has been intensively researched in various countries across the world for more than 30 years. The findings of this research have been summarized in several literature reviews. They reveal that awareness and knowledge among the population is rather low. People are neither aware of the relevance of hydrogen as a key component of a future sustainable energy system nor are they aware of the actual implementation of (national) hydrogen strategies [12,13]. Regarding the acceptance of hydrogen technology, the reviews demonstrate that the perceived costs, risks, and benefits are relevant influencing factors [12,14]. However, the focus of earlier studies was primarily on hydrogen cars and buses and the related infrastructure, although some also consider the acceptance of domestic applications, such as hydrogen boilers and hobs. In more recent studies, the focus is changing. They examine public perceptions and attitudes toward different hydrogen production pathways, such as "green" or "blue" [15–18], and the acceptance of hydrogen-related infrastructure measures, such as the construction of pipelines [19].

These general tendencies are supported by recent findings from Germany. They show that people's knowledge about hydrogen is still rather low [20] and only one fifth have heard of green hydrogen; in contrast, 85% have heard of hydrogen in general [17]. Accordingly, it is not surprising that a relatively large share of the population (24%–34%) does not have the confidence to assess the potential impact of using green hydrogen [17] or has no opinion about it (22%–39%) [20]. Despite this low level of knowledge and a widespread inability to express an opinion on the subject, a large share of the remaining population has a positive attitude toward the local deployment of green hydrogen [17] and expresses generally supporting attitudes toward green hydrogen [20]. However, major reservations tend to be observed when it comes to the acceptance of storage facilities [20] and the construction of pipelines [19] in the vicinity.

2.2. Hydrogen in the media: intensity and reasons for media reporting

One explanation for the low levels of knowledge and the reluctance of large public segments to express an opinion on the use of green hydrogen could be the way in which the media reports about such technologies and the associated discussions and processes. In the following, we summarize the findings of previous studies on the reporting on hydrogen in Germany, as there are virtually no international studies. There are two central findings.

First, various studies show that the level of reporting on hydrogen is rather low [21–23]. To adequately assess the amount of media coverage on hydrogen, it must be considered in relation to other topics. For example, Zimmer and Jänsch [23] show that the amount of news reporting on battery electric vehicles is increasing, while the reporting on hydrogen in the context of mobility remains small. This is also confirmed by more recent data on German media reporting between 2018 and 2020 [24]. In addition, Schiller and Klügel [25] find that topics such as mobility (21%), especially e-mobility, wind energy (18%), and energy grids (17%) account for larger shares of public broadcasting compared to hydrogen (10%). Furthermore, there is comparatively more reporting on imports of green hydrogen while other forms of hydrogen production (blue or gray hydrogen) are almost non-existent in the recent coverage [26].

Second, research indicates that different types of events can influence the reporting of hydrogen. While hydrogen-related events can lead to an increase in media coverage, at least temporarily [21,23], other events can also have an effect. For example, the Russian war against Ukraine, which can be characterized as a "focusing event" [27], has led to changes in the public discourse on the energy transition in general and also influenced the debate on hydrogen. Three shifts have been found in the German hydrogen media discourse following the Russian invasion of Ukraine [28]. First, there was a shift from sustainability considerations to security of supply. Second, discussions about new international energy partners for future German hydrogen imports became more prominent. Third, the Russian war appeared as a driver for hydrogen innovation (e.g., in the case of a push for hydrogen-readiness in new liquid natural gas (terminals). In sum, the war directed the German media discourse from internal hydrogen topics such as the NHS toward external topics related to the security of supply. However, their study provides little insight into the intensity of energy-related media coverage and its evolution [28].

2.3. Research questions and hypothesis

On the basis of existing research, and taking into account the research gaps mentioned above, we present the following research questions [RQs]:

RQ1: How intensively was the topic of hydrogen reported on compared to other subtopics of the energy transition?
RQ2: How has the intensity of reporting on the topic of hydrogen changed over recent years? To what extent can we observe event-driven ups and downs in the media coverage on hydrogen?
RQ3: How intensively was the topic of green hydrogen reported on compared to other production pathways?

Furthermore, we ask how media users perceive the reporting. Do they recognize how much attention the media pays to the various subtopics? It is known from agenda setting research that the perception of the intensity of reporting is important, because if people do not even notice that a certain topic is reported on more than others then it is unlikely that they will engage with the topic, and if they do not engage with a topic, then it can hardly be expected that they will form an opinion on it. Therefore, we ask the following question:

RQ4: Do citizens recognize the relative attention that the media devotes to hydrogen compared to other subtopics of the energy transition?

Based on the literature review, it can be assumed that green hydrogen is not covered prominently by the media, and considering the available research on knowledge and attitudes toward green hydrogen, it seems unlikely that the majority of citizens already had a firm stance on the issue when we started analyzing public opinion on green hydrogen in the summer of 2023. However, the available results also demonstrate that those who already have opinions on the topic have mainly positives ones. Moreover, it is plausible to expect that the Russian invasion of Ukraine and the associated debate about the future of energy supply in Germany may have stimulated the process of opinion forming. As a result of this process, the share of people who have an opinion on the subject might have increased. Accordingly, we ask the following question:

RQ5: What attitudes do respondents have toward the hydrogen infrastructure and toward the potential and challenges associated with the use of hydrogen (RQ5a), and have these attitudes changed over time (RQ5b)?

If people do not have much information on a particular topic, they can form an opinion by inferring it from existing attitudes on similar issues. Accordingly, one can expect relatively strong correlations between attitudes toward green hydrogen and attitudes toward the energy transition in general. Therefore, we state the following hypothesis:

H1. People with positive attitudes toward the energy transition have positive attitudes toward the infrastructure and the advantages potentials of green hydrogen and negative attitudes regarding the challenges related to the usage of green hydrogen.

Especially when people have not yet developed a clear idea of an object and therefore have no fixed attitudes toward it, the media may have considerable potential for influence. This assumption can be underpinned by various theoretical approaches. The media have the potential to create awareness for a new topic and put it on the agenda. Furthermore, they are especially effective in shaping schemes when the existing schemes are not well elaborated, and they have a high potential in creating frames when people still have not adopted a specific frame on a topic. All these effects can be explained by theories of information processing (for an overview and further literature, see Ref. [29]). Overall, it seems plausible that an opinion-forming process began after the start of the war, which was shaped by the media coverage. We therefore pose the following research questions:

RQ6: How have attitudes toward green hydrogen changed since the Russian invasion of Ukraine?

RQ7: How are these changes associated with citizens' communication behaviors and media use?

3. Method

This study uses a multi-method design that combines an automatized content analysis of German newspaper coverage and a three-wave panel survey of the German population.

3.1. Media content analysis

A media content analysis is a systematic method for examining media content, for example to identify topics in news coverage. It comprises several steps, starting with the selection of media and newspaper articles to be analyzed (sample), definition of the instrument and procedure for data collection, and the strategies for data analysis. These steps are explained in more detail in the following.

3.1.1. Media sample and article selection

The media sample consisted of three German newspapers: the leading tabloid, *Bild*, and the two most important quality newspapers, *Frankfurter Allgemeine Zeitung* (FAZ) and *Süddeutsche Zeitung* (SZ). The selected media aim at different target groups concerning political orientation and quality expectations. By selecting these newspapers, we wanted to ensure that the diversity of reporting on the topic was reflected in our sample. The articles were accessed via LexisNexis (Bild), via the newspaper's library archive (FAZ), and via subscription (SZ). The sample included 7649 articles published between June 1, 2021, and May 28, 2024, containing at least one mention of one of the following search terms: energy transition, energy supply, renewable energies, and hydrogen.

3.1.2. Instrument and procedure for data collection

The computer-assisted content analysis followed a dictionary approach utilizing the R package *quanteda* [30] to examine the coverage of hydrogen and four other energy-related topics: heat supply, electricity grid, wind energy, and solar energy. The dictionaries included wildcard characters to account for the high prevalence of closed compound words in German. For indicators with several (nonrelevant) meanings, the intended use of these terms in the sample was verified.

The mention of hydrogen was measured using five indicators. Additionally, ten subcategories with one indicator each were utilized to differentiate hydrogen production pathways [31]. Each pathway was measured with one bigram consisting of the respective "color" and the term hydrogen (e.g., "green hydrogen"). The other topics were measured with between four and 39 indicators each for heat supply (7) electricity grid (39), wind energy (4), and solar energy (12). A complete list of indicators for the categories is available in Table A1 in the appendix.

3.1.3. Data analysis strategy

All category occurrences were standardized to an average 500-word article to account for the variety of article lengths in the sample ($M = 738$ words, $SD = 469$, $n = 7649$). For further analysis, only such articles were used that contain at least five indicators of any of the five topics. They were assigned to the topic whose indicators appeared most frequently in the article. The articles about hydrogen were further analyzed regarding mentions of hydrogen "colors."

For a meaningful analysis, the data had to be aggregated. For this purpose, the overall study period was divided into 13 shorter periods lasting between two and three months (Table 1). Decisive for the definition of these periods were specific events that could have potentially influenced the hydrogen coverage. In addition, the field phases of the panel survey were considered. For the aggregation of data, the sum of the weighted articles for each topic was calculated for each of the 13 sections and weighted by the length of the respective section in days.

Table 1
Analyzed time periods.

	Dates	Description (Intern)
1	01.06. – 20.07.2021	Hydrogen action plan
2	21.07. – 26.09.	Election campaign
3	27.09. – 07.12.	Coalition formation
4	08.12. – 24.02.2022	Pre-war phase
5	25.02. – 03.06.	First reactions to the Russian invasion until EU sanctions against crude oil and oil products
6	04.06. – 26.09.	Further reactions to the war (e.g. destruction of Nord Stream I and II)
7	27.09.– 17.12.	1st part of energy crisis winter until opening of 1st LNG-terminal in Germany
8	18.12. – 01.03.2023	2nd part of energy crisis winter, 1st anniversary of beginning of war in Ukraine
9	02.03. – 29.06.	*Survey Wave 1* Debate about amendment to the Building Energy Law
10	30.06. – 08.09.	Continuation of debate until passing of the law
11	09.09. – 23.11.	*Survey Wave 2* Federal court verdict on climate- and transformation fond
12	24.11. – 24.02.2024	2nd anniversary of beginning of war in Ukraine, 2nd winter
13	25.02. – 28.05.	*Survey Wave 3* "Quiet phase" after uneventful winter/after energy crisis

3.2. Panel survey

A quantitative survey is a research method commonly used in the social sciences to empirical measure theoretical concepts, such as attitudes toward green hydrogen, within a defined population sample. This is achieved using a standardized questionnaire. In the case of a panel survey design, the same participants are assessed repeatedly at different time points, enabling the examination of individual-level changes over time.

3.2.1. Sample

The population's perspective was obtained through a three-wave online panel survey using the Online Access Panel from Bilendi, a professional market researcher (certified, 20252:2019). Based on a quota selection stratified by gender, age, and education, the initial sample comprised a total of 2701 people (50% women) from the German population. The participants were aged between 16 and 65 years (mean age: 42 years). Of the respondents, 41% had the highest German education degree, 33% had a medium education degree, and 26% had a low or no education degree. The first survey wave (t_1) was fielded between June 9 and June 29, 2023. The second wave (t_2), with 1843 participants, was conducted between November 23 and December 6, 2023. The third survey wave (t_3), with 1435 participants, took place between May 29 and June 12, 2024.

3.2.2. Data weighting

Even though the panel mortality rate, which refers to the loss of participants from wave to wave, was low, still shifts in the social composition of the participants were evident, particularly regarding age. While the proportion of older respondents increased from wave to wave, the proportion of younger respondents decreased (see.A2 in the appendix). Therefore, the data of the second and third waves were weighted so that the age distribution of the first wave was maintained in subsequent waves.

3.2.3. Measurement tool

The following section provides an overview on the operationalization and descriptive results of the theoretical concepts.

Attitudes toward green hydrogen, the central dependent variable of this study, were measured with three constructs. First, to determine how respondents rate the potential and challenges associated with the use of green hydrogen, six items on a 5-point scale (1 = fully disagree; 5 = fully agree) were used. Participants could also answer "do not know" (see Table 6). Explorative factor analyses confirmed the distinction between the potential and challenges (Table A3 in the appendix). Accordingly, two indices were formed for each survey wave: attitude toward the potential as well as attitude toward the challenges related to the usage of green hydrogen (Table 2). The third indicator measures people's attitudes toward the expansion of the hydrogen infrastructure on a 5-point scale (1 = fully reject; 5 = fully support) with two items, which were also combined into an index (Table 2).

In order to test the hypotheses, *attitudes toward the energy transition* were measured using two indicators. First, attitudes toward the expansion of the energy transition infrastructure were measured using an index consisting of four items, which summarizes support for the expansion of onshore wind power, solar parks, photovoltaic systems on roofs and facades, and the electricity grid on a 5-point scale (1 = fully reject; 5 = fully support). Second, people's attitudes toward the technological feasibility of the energy transition were assessed with one item on a 5-point scale (1 = fully disagree; 5 = fully agree), asking participants whether innovative technologies will make it possible to secure the energy supply entirely from renewable energies (Table 3).

3.2.4. Media and communication variables

To answer RQ4, respondents were asked how often (1 = never; 5 = very often) they perceived media reports on the various aspects of the energy transition (Table 4).

Table 2
Operationalization and descriptive results on attitude toward green hydrogen.

		t_1	t_2	t_3
Attitude toward the potential of the usage of green hydrogen				
Green hydrogen is indispensable for Germany's future energy supply.	M (SD)	3.7 (1.1)	3.6 (1.1)	3.6 (1.1)
Germany needs green hydrogen to achieve its climate goals.	M (SD)	3.6 (1.1)	3.5 (1.1)	3.5 (1.2)
The development of a green hydrogen economy is a great opportunity for Germany's economic development.	M (SD)	3.6 (1.1)	3,6 (1.1)	3.6 (1.1)
Germany can reduce its dependence on oil and natural gas with green hydrogen.	M (SD)	3.5 (1.1)	3,5 (1.1)	3.5 (1.2)
Index of the four items[a]	α	0.899	0.919	0.934
	M (SD)	3.6 (1.0)[b]	3.6 (1.0)	3.6 (1.1)
Attitude toward the challenges of the usage of green hydrogen				
Considerable imports are needed to meet the demand for green hydrogen in Germany.	M (SD)	3,6 (1,1)	3,7 (1,1)	3,7 (1)
It is far too expensive to use green hydrogen on a large scale.	M (SD)	3.4 (1.1)	3.5 (1.1)	3.5 (1.1)
Index of the two items	r	0.418	0.392	0.463
	M (SD)	3.5 (1.0)	3.6 (0.9)	3.5 (1.0)
Attitude toward expansion of hydrogen infrastructure				
Construction of pipelines for the transportation of hydrogen through the region in which you live	M (SD)	3.4 (1.2)	3.3 (1.2)	3.3 (1.2)
Construction of new production facilities for the generation of hydrogen near where you live	M (SD)	3.5 (1.1)	3.4 (1.1)	3.4 (1.2)
Index of the two items	r	0.650	0.698	0.726
	M (SD)	3.4 (1.0)	3.3 (1.1)	3.3 (1.1)

Note.
[a] Persons who only had an opinion on one of four items on the potential of green hydrogen or otherwise only answered "don't know" were set to missing in the overall index; Mean values (standard deviations) of variables measured on a scale from 1 (fully reject) to 5 (fully support).
[b] Reading example: In June 2023, agreement with the potential of the usage of green hydrogen, which was measured with a total of four items, was 3.6 on average this means people have a slightly positive attitude.

Table 3
Operationalization and descriptive results on attitude toward energy transition.

		t_1	t_2	t_3
Attitude toward expansion of energy transition infrastructure				
Construction of wind turbines near the place where you live (onshore)	M (SD)	3.3 (1.3)	3.2 (1.3)	3.2 (1.4)
Construction of solar ground mounted systems near the place where you live	M (SD)	3.5 (1.2)	3.5 (1.3)	3.5 (1.3)
Construction of photovoltaic plants on roofs and facades in your home town/ village	M (SD)	4.0 (1.1)	4.0 (1.1)	4.0 (1.1)
Construction of power lines through the region where you live	M (SD)	3.2 (1.2)	3.3 (1.2)	3.3 (1.2)
Index of four items	α	0.811	0.842	0.848
	M	3.5	3.5	3.5
	(SD)	(1.0)	(1.0)	(1.0)
Attitudes toward the technological feasibility of the energy transition				
Innovative technologies will make it possible to secure the energy supply entirely from renewable energies at all times.	M (SD)	3.2 (1.1)	3.1 (1.1)	3.2 (1.1)

Note: Mean values (standard deviations) of variables measured on a scale from 1 (fully reject/disagree) to 5 (fully support/agree).

To answer RQ7, different indicators for people's media use and communication behaviors assessed in wave two were used. First, it was measured how often (1 = never and 7 = daily) respondents obtained information on political issues either from traditional *mass media* (public television, private television, local newspapers, national newspapers and magazines, tabloid newspapers) or from *social media* (social networks, blogs, video platforms). For further analysis, they were composed into a maximum index. For the maximum index, the highest value mentioned by the respondents in the respective media group (mass media/social media) was used. Second, *incidental and targeted contact with news and information on the energy transition* was determined by one item each asking participants how often (1 = never and 5 = very often) they come across news or information on the energy transition online by chance and how often they intentionally search for news or information. Finally, the frequency of conversations (1 = never and 5 = very often) about the energy transition with family and friends as well as colleagues and acquaintances was assessed, the results of which were also composed into a maximum index (Table 4).

4. Results

To answer RQ1 and RQ2, the development of media coverage on hydrogen and the four other energy-related topics in the observed time period is depicted in Fig. 1.

RQ1 asked about the intensity of hydrogen reporting compared to other subtopics of the energy transition. Most of the time, hydrogen (red line) was on the second lowest rank; just the electricity grid saw fewer articles. Only at the very beginning of the analyzed time period was hydrogen among the most reported topics. Overall, it can be seen that there is continuous reporting on energy topics, but hydrogen is not a prominent topic aspect most of the time.

Furthermore, the graphs show that the media discourse on many energy-related topics changed somewhat with the start of the Russian invasion (in particular increased reporting on heat supply). Additionally, the time series shows one extreme peak in media intensity about heat supply. This is due to the discussions surrounding an amendment to the Building Energy Act (Gebäudeenergiegesetz) between March and the end of June 2023 (blue line).

RQ2 addressed the development of hydrogen media coverage and the impact of events on this development. The results show that the period between June and July 2021 differs significantly from the following periods. In this time hydrogen (red line) was rather prominently featured in the energy discourse (2nd highest number of articles per day). This finding can be traced back to the discourse surrounding the implementation of the NHS in the wake of the publication of the German national hydrogen action plan. After the federal election in September 2021, the intensity of hydrogen coverage dropped noticeably and remained at a low level. Even the Russian invasion of Ukraine in February 2022 did not change this – although the search for alternative energy sources was of great relevance at that time. The war and the resulting energy crisis had barely any impact on the intensity of hydrogen reporting; it remained rather constant for most of the observed time periods (end of February 2022 until end of November 2023). The small peak between November 2023 and February 2024 is due to a combination of several hydrogen-related events: the publication of Germany's new power plant strategy, which addressed, among other

Table 4
Operationalization and descriptive results on media and communication variables.

		t_1	t_2	t_3
Perceptions of media coverage on the different aspects of the energy transition[a]				
Wind power	M (SD)	2.8 (1.2)	2.6 (1.3)	2.5 (1.3)
Solar energy and photovoltaics	M (SD)	3.0 (1.3)	2.8 (1.3)	2.7 (1.3)
Hydrogen	M (SD)	2.4 (1.2)	2.3 (1.2)	2.1 (1.2)
Electricity grids	M (SD)	2.7 (1.2)	2.5 (1.2)	2.4 (1.2)
Heat supply	M (SD)	3.3 (1.4)	2.8 (1.3)	2.5 (1.3)
Media use for political information[b]				
Public television and their online offerings	M (SD)		4.1 (2.1)	
Private television and their online offerings	M (SD)		3.6 (2.0)	
Tabloid newspapers and their online offerings	M (SD)		2.3 (1.8)	
Local and regional newspapers and their online offerings	M (SD)		3.5 (2.0)	
National newspapers and news magazines and their online offerings	M (SD)		2.9 (1.9)	
mass media use (max index)	M (SD)		5.0 (1.8)	
Facebook, Twitter or other social networks	M (SD)		3.7 (2.4)	
Blogs and online forums	M (SD)		2.2 (1.8)	
YouTube or similar video platforms	M (SD)		3.2 (2.1)	
social media use (max index)	M (SD)		4.2 (2.3)	
Incidental and targeted contact with news and information on the energy transition[a]				
How often do you come across news or information about the energy transition by chance, even though you actually went online for a different reason?	M (SD)		2.8 (1.1)	
How often do you search the media specifically for news or information on the energy transition?	M (SD)		2.3 (1.2)	
Conversations about the energy transition[a]				
Conversations about the energy transition with family and friends	M (SD)		2.8 (1.2)	
Conversations about the energy transition with colleagues and acquaintances	M (SD)		2.5 (1.2)	
interpersonal communication (max index)	M (SD)		2.9 (1.2)	

Note.
[a] Mean values (standard deviations) of variables measured on a scale from 1 (never) to 5 (very often).
[b] Mean values (standard deviations) of variables measured on a scale from 1 (never) to 7 (daily).

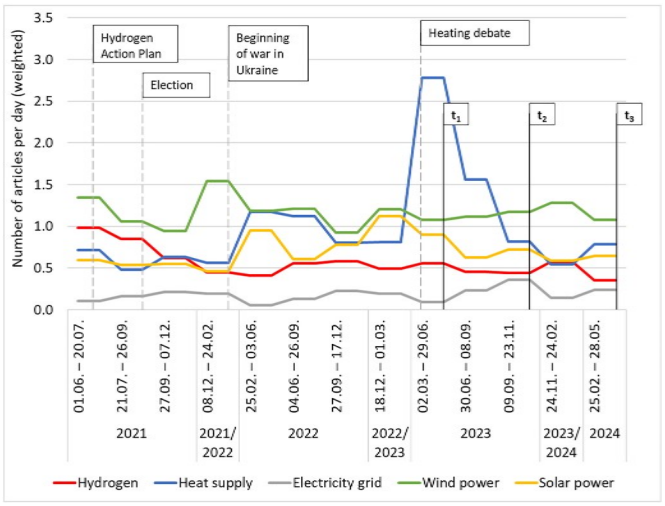

Fig. 1. Time series of media coverage about energy topics.

things, hydrogen-ready power plants [32]; a concept for the development of the German hydrogen network [33]; and the dismissal of a high-ranking employee of the Federal Ministry for Digital and Transport Affairs as a result of the so-called "hydrogen affair" [34]. However, both peaks in hydrogen reporting are significantly smaller than the peak observed for the heating debate. Obviously, none of the hydrogen-related events was noteworthy enough to clearly shape the media coverage.

Fig. 1 also provides the context for the three survey waves (t_1 to t_3). At the time of the first survey (t_1), the debate about heating regulation (blue) was the dominant energy-related topic by a large margin, while hydrogen (red) remained in second-to-last place. The time before the second survey (t_2) is marked by a decline in articles on heat supply after the conclusion of the legislation. Hydrogen (red) was again the topic with the second lowest intensity of media coverage. The ranking of the topics remained unchanged between the second and third survey (t_3).

RQ3 addresses the intensity of media reporting on different hydrogen production pathways (i.e., colors of hydrogen). Fig. 2 depicts the time series of total hydrogen coverage (red), as well as those for green and blue hydrogen. As the other pathways were barely mentioned in the sample, they were grouped together (gray line). Looking at the strong similarities between the time series for hydrogen in general and green hydrogen, it becomes clear that current media coverage practically equates hydrogen and hydrogen from renewable sources. All other colors of hydrogen are most of the time almost ignored.

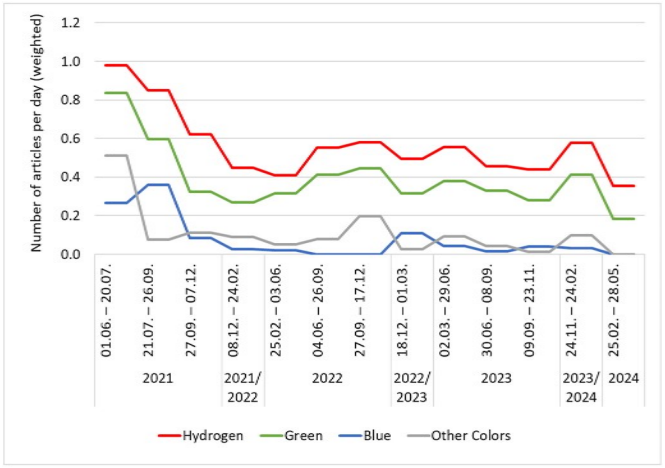

Fig. 2. Time series of different hydrogen production pathways (colors of hydrogen).

With regard to RQ4, it can be seen that almost all participants in all survey waves felt able to estimate the perceived amount of media coverage of energy-related topics. Only a few respondents did not answer this question (<4%). The results in Table 5 show that the perceived amount of coverage decreased for all aspects. This finding is only partially in line with the results of the content analysis (Table 5). In fact, only between the first and the second wave did the intensity of the coverage decrease significantly; between the second and the third wave the amount of coverage remained largely stable.

Beyond that, the correlation coefficients Rho indicate a positive relationship between the actual amount of coverage and the rank order of the perceived amount of coverage. This shows that people are able to roughly estimate the relative media attention given to the different subtopics. This constitutes a critical prerequisite for the presumed media effects. If individuals are not aware of the extent to which various topics are covered in the media, it is unlikely that such reporting would exert a significant influence on recipients.

However, the strength of the correlation varied between the waves. A higher correlation was only observed when there were clear differences between the real extent of reporting on the various aspects (t_1 in Fig. 1). For the second and the third wave, when the media differences were smaller, the correlations with the perceptions were also weaker.

To answer RQ5, we examined people's attitudes toward the use of green hydrogen and hydrogen infrastructure, and how they developed over time. Previous studies have shown that many people do not have attitudes toward hydrogen. Accordingly, we are not only interested in the valid answers (1 = fully disagree; 5 = fully agree) but also in the answers of those who felt unable to state an attitude in relation to the measured items.

Regarding attitudes toward the potential and challenges associated with the use of green hydrogen, Table 6 shows three key findings. First, for all items, many people chose the "don't know" option (23%–35%). Evidently, many respondents were unsure whether to agree or disagree with the statements, particularly regarding the challenges associated with green hydrogen. This high proportion is remarkable because the scale also included the option "ambivalent." Second, the majority of those who reported an opinion recognize not only the potentials of green hydrogen but also the challenges associated with the technology. Third, the distribution of responses remained largely unchanged across the three survey waves.

Attitudes regarding the expansion of hydrogen infrastructure can be seen in Table 7. The main differences compared to Table 6 are that the share of people without an attitude is lower and that attitudes toward hydrogen infrastructure are getting slightly more negative over time.[1] Above all, the substantial proportion of individuals lacking a definitive attitude toward hydrogen presents significant opportunities for media influence, as individuals with ambiguous positions are theoretically more susceptible to persuasion.

To test the hypothesis, that people derive their attitudes towards hydrogen from other energy-related attitudes, correlations between the two indicators for positive attitudes toward the energy transition (expansion of the energy transition infrastructure and technological feasibility of the energy transition) and the three indicators for attitudes toward hydrogen were calculated for each wave.

As the findings in Table 8 show, the hypothesis is essentially confirmed. Across all measurement points, positive correlations between attitudes toward the energy transition and attitudes toward hydrogen were found, with the strongest correlations for infrastructure measures. This confirms that people infer from existing attitudes toward expansion of the energy transition infrastructure to attitudes toward

[1] The results of two paired *t*-test, which tests whether the mean difference between the two measured values is zero. First *t*-test: $M_{t1} = 3.44$, $M_{t2} = 3.35$, $n = 1556$, $p < 0.001$; Second *t*-test: $M_{t2} = 3.35$, $M_{t3} = 3.32$, $n = 1198$, ns.

Table 5
Development of the intensity of coverage and the perception of the intensity on different aspects of the energy transition.

Aggregated days Time of survey		Heat supply	Solar energy and PV	Wind power	Electricity grids	Hydrogen	Rho
119 days	Articles/day	2.78	0.90	1.08	0.09	0.55	0.80
June 2023	M (SD)[1]	3.29 (1.37)	3.00 (1.30)	2.79 (1.25)	2.70 (1.24)	2.44 (1.22)	
75 days	Articles/day	0.81	0.72	1.17	0.36	0.44	0.60
Nov/Dec 2023	M (SD)	2.79 (1.29)	2.76 (1.31)	2.57 (1.25)	2.52 (1.23)	2.27 (1.20)	
93 days	Articles/day	0.78	0.65	1.08	0.24	0.35	0.50
June 2024	M (SD)	2.50 (1.28)	2.65 (1.29)	2.49 (1.27)	2.35 (1.22)	2.11 (1.18)	

Note: Number of participants in the survey June 2023 (n = 2615–2640), Nov/Dec 2023 (n = 1769–1785), June 2024 (n = 1392–1400); [1]Mean values (standard deviations) of variables measured on a scale from 1 (never) to 5 (very often); Rho = correlation between the rank order of the real amount of coverage and the rank order of the perceived amount of coverage.

Table 6
Attitudes toward the potential and challenges of using green hydrogen.

	Time of survey	disagree	ambivalent	agree	don't know
		%	%	%	%
Attitude toward the potential of green hydrogen					
Green hydrogen is indispensable for Germany's future energy supply.	t_1	12	23	40	26
	t_2	12	22	38	28
	t_3	13	24	36	28
The development of a green hydrogen economy is a great opportunity for Germany's economic development.	t_1	10	22	45	23
	t_2	10	23	41	26
	t_3	10	22	42	26
Germany can reduce its dependence on oil and natural gas with green hydrogen.	t_1	10	21	47	23
	t_2	11	20	44	25
	t_3	10	19	46	24
Germany needs green hydrogen to achieve its climate goals.	t_1	12	21	43	25
	t_2	12	21	41	26
	t_3	12	22	40	27
Attitude toward the challenges of green hydrogen					
Considerable imports are needed to meet the demand for green hydrogen in Germany.	t_1	10	22	35	34
	t_2	7	23	36	34
	t_3	8	23	34	35
It is far too expensive to use green hydrogen on a large scale.	t_1	13	15	31	31
	t_2	12	23	34	32
	t_3	13	21	35	31

Note: disagree (1 = fully disagree; 2 = rather disagree); ambivalent (3 = partly/partly); agree (4 = agree; 5 = fully agree); due to roundings, the sum of listed individual positions may be higher/lower than 100%.

Table 7
Attitudes toward expansion of hydrogen infrastructure.

	Time of survey	oppose	ambivalent	support	don't know
		%	%	%	%
Construction of pipelines for the transportation of hydrogen through the region in which you live	t_1	17	29	41	13
	t_2	18	29	38	15
	t_3	21	28	36	16
Construction of new production facilities for the generation of hydrogen near where you live	t_1	14	29	44	13
	t_2	17	27	41	15
	t_3	18	27	41	15

Note: oppose (1 = fully reject; 2 = rather reject); ambivalent (3 = partly/partly); support (4 = rather support; 5 = fully support); due to roundings, the sum of listed individual positions may be higher/lower than 100%.

Table 8
Correlations between attitudes toward energy transition and attitudes toward hydrogen.

	Attitude toward expansion of energy transition infrastructure[1]			Attitude toward technological feasibility of the energy transition[2]		
	t_1	t_2	t_3	t_1	t_2	t_3
Attitude toward expansion of hydrogen infrastructure[a]	**0.60**[c]	**0.68**[c]	**0.71**[c]	0.34[c]	0.36[c]	0.45[c]
Attitude toward the potentials of the usage of green hydrogen[b]	0.52[c]	0.56[c]	0.54[c]	0.44[c]	0.44[c]	0.54[c]
Attitude regarding the challenges related to usage of green hydrogen[b]	0.03	−0.04	−0.01	0.02	−0.04	−0.10[c]

Note.
[a] 1 = low support to 5 = strong support.
[b] 1 = low agreement to 5 = strong agreement.
[c] $p < .01$.

expansion of infrastructure for the use of hydrogen. In contrast, hardly any correlations were found between attitudes toward the energy transition and attitudes toward the challenges associated with the use of green hydrogen. This is due to the fact that it is much more difficult to infer specific challenges associated with a new technology from general attitudes toward other technologies.

The findings in Tables 6 and 7 demonstrate that the distributions of attitudes in the aggregate are relatively stable over time. The absence of dramatic changes in this regard can be largely attributed to the fact that hydrogen never became the focus of media attention throughout the entire study period, resulting in only marginally engagement from the public with the topic. However, it is unclear to what extent changes in attitudes at an individual level take place and to what extent they can be linked to communication behaviors and media use. To answer RQ6, the following section focuses on attitudes toward the *potentials of green hydrogen*. We do this for two reasons. First, the proportion of people answering "don't know" is lower than for the challenges. Obviously, it is quite difficult to form an opinion regarding the challenges. Therefore, it is reasonable to expect first of all media effects on the assessment of potential. Second, as the attitudes toward the hydrogen infrastructure are strongly related to the attitudes toward other infrastructure measures (see Table 8), it is less plausible to expect media and communication effects on infrastructure measures than on the assessment of potential.

In general, studies on attitude changes at the individual level only consider the changes for those people who already have an opinion at t_1. However, this approach falls short in the case of issues on which people do not yet have an opinion or when this opinion is not yet firmly stable. For this reason, the following observations also explicitly consider those who did not answer ("don't know"), which results in a total of six groups

of attitude constellations from t_1 to t_2 (see Fig. 3).

As the findings in Fig. 3 illustrate, the vast majority (59%) remain stable in their attitude toward the potential of green hydrogen, regardless of whether this is constantly positive, ambivalent, or negative (yellow). In contrast, only a very small share of respondents changed their already existing attitudes in the sense of worsening (orange: 5%) or improvement (green: 4%). In addition, the findings show how important it is to consider those who answered "don't know" at one or both points in time, as this affects a total of 32% of respondents. Of these, the largest group are those who constantly have no attitude toward the potential of green hydrogen – at both waves, they responded with "don't know" (gray). In contrast, 9% show an attitude formation from "do not know" at t_1 to an evaluation at t_2 (blue), while at the same time 10% show an attitude loss (purple), which indicates an uncertainty of the evaluations expressed at t_1.

In order to answer RQ7, we explore the relationship between these changes and citizens' communication behaviors and media use with cross-tabulations (Table 9). We are doing this to investigate if we can find any evidence that the media might influence people's attitudes towards hydrogen. Several key observations emerge from the analysis.

Similar media usage and communication behaviors can be seen within two groups, each consisting of three types of people with specific patterns of attitude change. On the one hand, the first groups (Table 9, columns 1–3) include individuals whose initial attitudes remained unchanged as well as those whose original attitudes either deteriorated or improved. All three groups exhibit a high frequency of mass media usage (approximately 80% engaging at least several times per week) to stay informed about political issues, such as the energy transition. Social media is also a common source of political information for these groups. Additionally, topic-specific communication behavior reveals further similarities: the energy transition is frequently discussed in personal conversations by 30%–41% of individuals; 28%–36% regularly encounter information on the energy transition incidentally, while one-fifth to one-quarter actively seek information on the topic. About one-fifth also frequently perceive the issue of hydrogen in the media.

On the other hand, in the second group (Table 9, columns 4–6), notable similarities are also found among individuals who constantly do not report an attitude, those who have recently formed one, and those who have lost it. These three groups display significantly lower levels of political information-seeking behavior, both generally and in relation to the energy transition. For most people in these groups, the energy transition is not a relevant media topic. For just 8%–15% it is a frequent topic of conversation; only 13%–17% frequently encounter the topic incidentally, and even fewer (2%–8%) actively seek information. These groups perceive the topic of hydrogen to receive minimal attention in the media.

Overall, the findings indicate that media use and personal conversations are more likely to reinforce or change *existing* attitudes rather than contribute to the formation or loss of attitudes.

5. Discussion

The starting point of this paper was the question to what extent the current discussions and activities regarding hydrogen as a core element of the future energy supply in Germany have also reached the public. To address this, this paper presents actual findings from an automated content analysis of 8.059 news articles, published between June 1, 2021, and May 28, 2024, and a three-wave panel survey conducted in 2023 and 2024. Overall, our study reaffirms several findings reported in previous analyses on German news reporting as well as from German opinion polls. Nevertheless, the study yields additional findings that extend beyond the current state of research. The analysis elucidates the conditions under which attitudes toward hydrogen are formed and explains the roles that pre-existing attitudes, media coverage, and media consumption may play in this context.

Our study confirms that there is constant reporting on hydrogen in the news, which is predominately focused on green hydrogen, as other recent studies have also shown [26,28]. Even an external shock, such as the Russian war on Ukraine, did not lead to more intense media coverage on hydrogen. It constantly remains at a rather low level, especially in relation to other energy-related topics, mirroring previous findings [23, 25].

Thus, hydrogen remains a niche topic in the energy-related media discourse. As the combination of content analysis and survey data in this paper shows, this is also consistent with the public's perception of energy reporting. At all times, hydrogen is the second least perceived topic in the reporting compared to other topics such as heat supply, solar energy, or wind power. This may also explain the uncertainty or lack of attitudes toward the topic observed in the survey data. This applies in particular to attitudes toward the challenges of using green hydrogen. However, the proportion of those who answered "don't know" was also quite high when it came to the presumed potential of hydrogen. Clear attitudes were most likely to emerge regarding infrastructure measures for the expansion of hydrogen. However, in view of the high correlations with attitudes toward other infrastructure measures, it can be assumed that these serve as anchors. Overall, the distribution for all attitudes remains more or less stable over time.

This study also provides insight into how attitudes toward the potentials of the use of green hydrogen were formed or lost over time on the individual level and what role media use and communication behaviors can play in this context. Here, the findings showed very clearly that the great majority of respondents remained constant in their

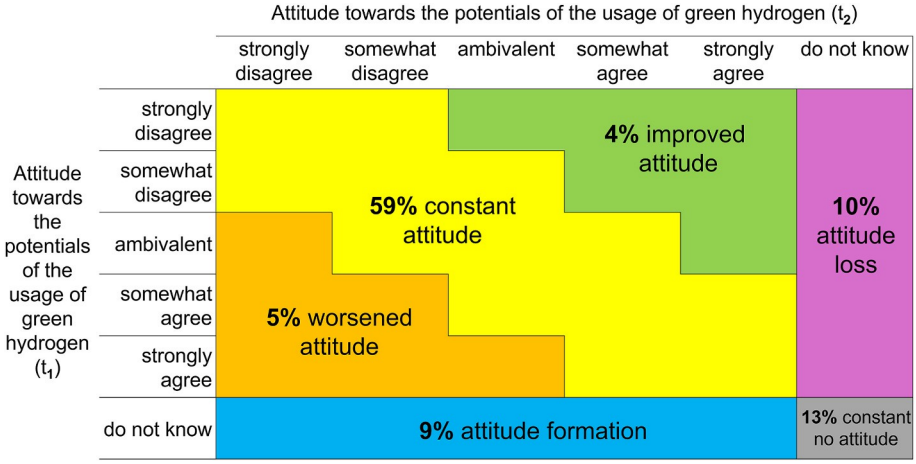

Fig. 3. Attitude changes at the individual level.

Table 9
Communication behaviors, media use, and attitude development toward hydrogen.

		constant attitude	worsened attitude	improved attitude	attitude formation	attitude loss	constant no attitude	
		n = 1096	n = 90	n = 64	n = 159	n = 192	n = 242	
		%	%	%	%	%	%	**p**
Use of mass media for political information	at least several times a week	79	80	81	59	61	57	<0.001
	less often	21	20	19	41	39	44	
Use of social media for political information	at least several times a week	58	58	69	52	45	47	<0.001
	less often	42	42	31	48	55	54	
Conversations about the energy transition	often	40	30	**41**	15	13	8	<0.001
	less often	60	70	59	85	87	92	
Incidental contact with energy transition information	often	28	30	36	17	14	13	<0.001
	less often	72	71	64	83	86	87	
Targeted search for energy transition information	often	20	18	**25**	8	4	2	<0.001
	less often	80	82	75	92	96	98	
Perception of hydrogen issue in the media	often	22	20	**26**	5	4	1	<0.001
	less often	78	81	74	95	96	100	

Note: Due to roundings, the sum of listed individual positions may be higher/lower than 100%.

attitudes. Comparatively few formed or lost an attitude; even fewer changed their existing attitudes. Regarding the role of interpersonal communication and media use, the presented data indicate that both were more likely to reinforce or change people's attitudes as these people actually came into contact with news and information related to the energy transition. In contrast, people without attitudes or with weak attitudes hardly came into contact with the topic, either through the media or through conversations. This finding is particularly significant, as individuals without firmly established attitudes are generally more susceptible to media influence. However, since these groups tend to consume less content related to the topic, the potential for influence remains unrealized. The question of how these groups can be reached through communication therefore remains relevant.

Low media coverage shows that the controversial discussions in science and politics about hydrogen have not yet reached the public. This is also reflected in attitudes. In particular, it seems difficult for people to assess the challenges. As different political actors are interested in promoting the production and use of green hydrogen for different – sometimes even conflicting – reasons, the challenges associated with this strategy may still not be prominently discussed. Accordingly, people are more familiar with the opportunities than the challenges. However, more in-depth analysis of the reporting is needed to verify this statement.

The results also illustrate how important it is to investigate those who have no opinion. The results show how difficult it is to reach this large group with specific information on the energy transition. Their general political media use is also lower, but a considerable group of undecided people can at least be reached via traditional media and social media. It is therefore to be expected that an opinion-forming process will only intensify if the topic is discussed very prominently in the media over a longer period of time. The general formation of opinion on the topic of "green hydrogen" will therefore depend heavily on whether this increased reporting will be associated with positive developments or implementation difficulties. It is concerning that increased media coverage may predominantly occur when problems and conflicts arise, as media logic tends to prioritize negative and contentious issues. If this proves to be the case, there is a risk that individuals who have not yet formed an opinion may develop negative attitudes. Should such a development take place, and if public protests are organized at locations that are intended for the construction of electrolysers, storage facilities, or pipelines, this could negatively affect political support for hydrogen projects.

However, as the topic of hydrogen has received relatively limited media coverage so far has resulted in many people not yet forming strong opinions or maintaining a generally positive stance toward the technology, which is expected to significantly contribute to a secure energy supply without harmful emissions or waste disposal challenges. Moreover, as hydrogen technology has so far not come to the attention of a critical public, there is hardly any significant resistance to political decisions in this area at the moment. While this creates a favorable situation for policymakers, industry, and the scientific community, it is important that stakeholders do not become complacent. Instead, they should use this period of relative calm to proactively prepare for potential objections and resistance which will certainly arise sooner and later.

Finally, the results underline the relevance of survey studies over time, which have hardly been carried out to date. They not only make it possible to observe changes in attitudes but also offer the opportunity to investigate possible causes and develop suitable communication strategies.

This study is not without its limitations. First, the content analysis' dictionary approach brings inherent inaccuracies because topics are reduced to individual words, which means different wordings cannot easily be accounted for. Second, the connection between media data and survey data could be improved. The selected newspapers account for some of the most popular German news sources, but they do not represent the full media spectrum available. Additionally, the survey did not contain questions about the participants' use of these newspapers specifically.

CRediT authorship contribution statement

Dorothee Arlt: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Marius Becker:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jens Wolling:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

For the revision of this work, the authors have used ChatGPT to improve the language, grammar and readability of the rewritten

paragraphs. We also used DeepL to translate individual paragraphs for the Action Letter from German into English. The authors take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dorothee Arlt reports financial support was provided by Federal Ministry of Education and Research. Marius Becker reports financial support was provided by Federal Ministry of Education and Research. Jens Wolling reports financial support was provided by Federal Ministry of Education and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements section

The paper was written as part of the transdisciplinary research project “Wissenschaftskommunikation Energiewende” (translated: Science Communication Energy Transition) that is funded by Federal Ministry of Education and Research (Nb. 03SF0625E).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.11.380.

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