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Review Article

Users in the design of Hydrogen Energy Systems: A systematic review

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HIGHLIGHTS

- 152 publications on Hydrogen Energy Systems end users were reviewed.
- Publications mainly focus on improving technology adoption.
- Final users are mostly perceived as a barrier.
- The study offers an update on determinants of Human Technology Relationship.

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ABSTRACT

The energy transition is a major societal issue to which hydrogen energy can make an important contribution. If the technical aspects of hydrogen energy seem paramount, it is also important to focus on the end users of these future systems. Indeed, users play an important role in the success of energy systems: they may not accept it, they may not use it as intended. But not only, users can also be a source of innovation. Thus, it is possible to mobilize different approaches, which if they are all legitimate, do not have the same efficiency. In this systematic review of the literature, which combines lexical analysis and data analysis of 152 publications, we identify the approaches implemented to take into account users in Hydrogen Energy Systems. Our results indicate that final users are mostly perceived as a barrier to the deployment of Hydrogen Energy Systems, or as a parameter to be assessed rather than as a resource for the design. Researches have mainly the aim of improving technology adoption. Since Hydrogen Energy Systems are emerging, we recommend focusing studies on upstream user research aimed at stimulating and enhancing technologies and systems design. We also recommend increasing the share of study which focus on the case of hydrogen energy stationary applications and buildings.

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Contents

Introduction

Humanity is in danger. In short, this is the message of more than 15,000 scientists in an article entitled "World Scientists' Warning to Humanity: A Second Notice " [1]. Their observation is that the consequences of human activity on the environment lead to exceeding the capacity of eco-systems to guarantee living conditions for humanity. Greenhouse gases, in particular carbon dioxide emissions must be reduced to limit one of the main consequences of human activity: climate change. Additionally, pollution, scarce fossil energy sources and energy security are some of the many other reasons that led to a consensus on the need for an Energy Transition [1] – switching from a highly carbonated energy system to a more sustainable one –.

This transition context is calling for the reduction of energy consumption and a diversification of energy sources, especially with Renewable Energies [2] which are decentralized and variable, implying that they are not necessarily produced when and where they are consumed. This increase in the share of Renewable Energies calls for flexibility solutions to match energy production with energy consumption [2,3].

Hydrogen Energy has been identified as a potential key factor to address the energy transition [4], because it offers great storage and flexibility capacities that cannot be achieved with electricity. Indeed, it can be stored in large quantities and over long periods, it can be obtained from different sources (renewables and fossils) and with different processes (electrolysis, reforming etc.) [3], and it can be used by combustion (to get mechanical energy and heat) or by electrochemical conversion (to get electricity and heat). For these reasons, hydrogen energy is seen as a possible way to secure renewable energies and to contribute to the Energy Transition. Hydrogen energy is being considered for:

- Transport with light vehicles [5,6] and heavy vehicles [7];
- Stationary applications, for instance energy autonomy for buildings [8] or for non-interconnected areas [3];
- Integration in centralized energy networks [4].

These different applications of hydrogen energy will be at some points interacting with end users. Thus, a whole body of research on Hydrogen Energy Systems addresses end users or "public" related issues. Reviews of the literature regarding Hydrogen Energy users have focused on acceptance [9–12]. They have summarized major trends in results and highlighted methodological and theoretical limitations of hydrogen energy acceptance studies. The purpose of this article is (a) to understand how researches has dealt with users in Hydrogen Energy Systems, (b) to make an updated inventory of the main results, and (c) to discuss the identified approaches in order to make recommendations on how to manage the Human Technology Relationship – the way human and technology interact [13] – in Hydrogen Energy Systems design.

To study these points, a systematic literature review is presented in this article. In section Users in the design of energy system, we introduce the importance of users in the design of energy systems. In section Method, we will depict the method. Then, in section Results we will present study results. At last, in section Discussion, we will discuss our results to conclude with recommendations.

Users in the design of energy system

Users in energy systems success

It is recognized that the role of users is of great importance in the success of energy projects, according to some authors, they have as much influence as technologies [14]. Technologies may not be accepted. This was the case with the deployment of wind farms, which have sometimes been the occasion of strong rejections from local populations [15,38]. Moreover, being accepted and used is not a sufficient criterion of success. It is important to pay particular attention to the behaviours and uses generated by technologies. Thus, in the building sector, experiments aimed at reducing energy consumption has taken place with a focus on the energy efficiency of buildings and equipment. Knowing that residents' behaviour is an important source of uncertainty and can strongly affect energy consumption [16,17], the expected reductions in consumption have not been observed [18,19]. This gap can be explained by the differences between users' actual activities and needs, and building designer representation of users' activities and needs, which lead to a lack of the conformation of the users to the instructions of use of the building and equipment's [20]. Another hypothesis is that inhabitants are subject to behavioural spillover [21], suggesting the existence of a moral compensation: when a morally positive action (e.g. invest in energy efficiency equipment) is used to legitimize a morally less positive action (e.g. no longer monitor energy consumption).

These phenomena reflect a defect in the Human Technology Relationship and emphasize the importance that must be placed on users, to ensure that Energy Systems are accepted and used in a desirable way. This calls for a reflection on the approaches used to manage the Human Technology Relationship in Hydrogen Energy Systems design. In the next paragraph we briefly present different approaches to take into account users in technological development, by focusing on their goals and their temporality.

Users in technological development

Improve technology adoption by evaluating the compatibility of technology and humans

One first and customary approach adopted in managing Human Technology Relationship consists of evaluating the compatibility of technology and humans or humans' reaction to technologies. In this approach, the technology is designed initially without integrating the user. Thereafter, users and technology compatibility is studied, to eventually slightly adjust the technology or its deployment modalities (communication, price etc.) to the users, the goal being to improve technologies adoption.

In the field of psychology, the concepts of *functional acceptance* and *social acceptance* [13,22] are used to examine technology compatibility with users' abilities, and technology acceptance in social context. The idea is that the better the compatibility between the technology and the user's capabilities and social environment, the more important is its adoption. These elements are used to estimate use or intent to use. For instance, Toft et al. [23] conducted a study to assess the acceptance of the smart grid technology, their results indicate that smart grid technology acceptance is determined by personal norm, so they recommend communicating on technology's individual and public benefits. In the case of economics, the *willingness to pay* is investigated by estimating the price that users are willing to pay for a good or a service, and the factors that determine it. For example, Sundt and Rehdanz [24] studied consumers' *willingness to pay* for renewable electricity and showed that the price consumers are willing to pay varies according to the energy sources and individual and household characteristics. Here the human is considered as a parameter to be mastered in order to guarantee the success of the technology. Such approaches match with the technology driver innovation strategy which consists to create added value through heavy technological research [25]. This strategy proposes to advise on technology's deployment modalities or on slight but costly and time-consuming modifications [26] of the technology itself.

Design technology with deep human understanding

A second approach of managing human technology relationship consist in understanding users to develop technologies. In this approach user research is conducted to understand user behaviour, activity, needs, representation, etc., to fuel the design process. Users can also be directly integrated in the design process. Here, the goal is twofold: relate to user knowledge to design adapted technology and relate to user knowledge to foster innovation. The approach refers to *user-centered design*, described in the case of interactive systems in the ISO 9241–210:2019. It is a comprehensive approach that aims to shape the technology to the user. For example, Meurer et al. [27] have conducted interviews on eco-feedback with the elderly. Their results allowed them to identify the characteristics of elderly users (e.g. give users the opportunity to understand their behaviour instead of advising on desired behaviour), these data are to be used in the design of eco-feedback tools applied to transport. This approach is congruent with the market reader or need seeker innovation strategy which consists for the first to create added value by transforming existing technologies to users expressed needs, and for the second to seeks innovation by relating on users' needs and uses understanding to lead product development. Jaruzelski et al. [25] indicate that innovation strategies based on user needs research are the most efficient. Further, it is a source of disruptive uses innovation that is to be successful in the short term [49,50]. Considering users' characteristic allows both to innovate and to propose technologies that fit users' particularities. In this approach, humans are considered as a resource on which to rely during the design process.

We presented two conceptions of considering humans' place in technological development. In one case it is an obstacle to overcome, in the other it is a resource on which to rely. This has very practical implications for the success of technological systems and it also highlights ideological differences. In the first case, when improving technology adoption by evaluating technology compatibility with humans, it is about supporting the technology, users being considered here as an externality of the technology. Whereas in the second one, when designing technology based on human understanding, the technology is an instrument, it serves the users.

When to integrate users

Both approaches can take place upstream or downstream of technology development. If we consider the technological development process as a continuum from its earliest stage where fundamental research is turned into applied research or development, to the moment a technology is deployed to the market, it is possible to include users' consideration at every moment. However, the earlier users are taken into account the greater are the capacities of action [28,29], and the lower are the costs associated with technology adaptation [26].

If intervening upstream in the technological development makes it possible to improve intervention efficiency, it does not preclude the establishment of a combined approach which integrates users as soon as possible to feed the design process, and which is later oriented toward an evaluation of users adoption to finely adjust the technology to particularities of the situation. This is particularly relevant when we consider that, the Human Technology Relationship is dynamic, it evolves with time and it has spatial and cultural specificities [13,30].

As we have shown, users can be included in the technological development in a perspective of evaluating user adoption or enhancing the design process, whether upstream or downstream. In Fig. 1, we summarize the four types of strategies that can flow from our analysis regarding strategies' goal and temporality:

- Strategy 1 (upstream evaluation) corresponds to an evaluation of users' reaction to an inexistent or emergent technology (e.g. evaluating acceptability of a future hydrogen filling station)
- Strategy 2 (downstream evaluation) corresponds to an evaluation of users' reaction to a developed or already deployed technology (e.g. evaluate acceptance of an existing hydrogen filling station)
- Strategy 3 (upstream understanding) corresponds to understanding users' needs toward a non-existent or emergent technology (e.g. relating to users' needs to design a hydrogen filling station)
- Strategy 4 (downstream understanding) corresponds to understanding users' needs toward a developed or already deployed technology (e.g. understanding users' unsatisfied or fulfilled needs toward an existing filling station)

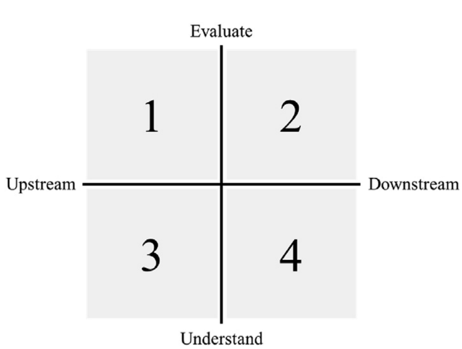

Fig. 1 – Categorisation of user integration in technological development.

Method

Data collection

Documents were collected through two databases searching related to hydrogen energy and Human Technology Relationship issues (see Fig. 2). Databases searching covered the oldest publications recorded until January 2018 on the following online databases: Academic Search Index, Complementary Index, Science direct, Academic OneFile, Psyc Info, BASE, Social Sciences Citation Index and Directory of Open Access Journals. The search procedure allowed to identify 2238 publications with the following keywords in title or abstract: hydrogen, fuel cell, preference, acceptance, acceptability, willingness, perception, attitude, user needs, expectation, anticipation, user requirements, prospective and forecasting. Duplicates were removed, and 1318 publications were excluded through the screening phase (exclusion of non-compliant publications based on title and abstract) and 31 through the scanning phase (exclusion of non-compliant publications based on the full publication):

- 1312 did not concern the users.
- 6 did not concern hydrogen energy
- 8 were not written in English
- 16 were not scientific material
- 8 had no related document

152 publications were finally included in the study (see Appendix for the list of publications included in the study), with 150 included in the lexical analysis (2 publications had no abstract available) and 148 were included in the data analysis (4 publications were not fully available).

Lexical analysis

We proceeded to a lexical analysis of the publications' abstracts with the objectives of highlighting the most important and used words and thematic clusters to identify publications approaches. We chose to limit analysis on abstracts because they are a concise and scripted, but complete, rather homogeneous and rigorous summary of the publication [31].

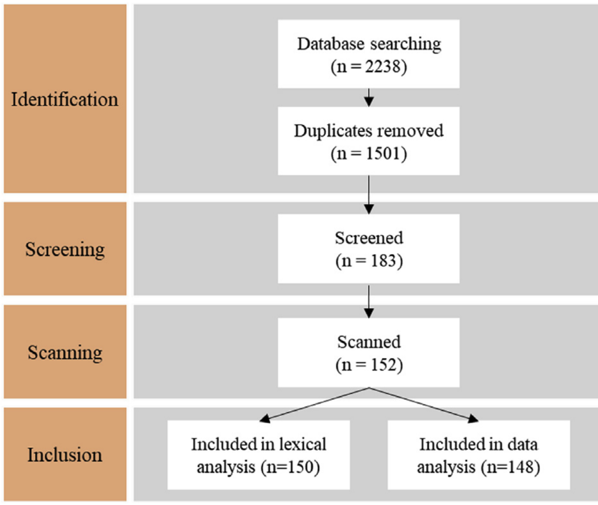

Fig. 2 – Data collection process.

This type of analysis is used to distinguish the corpus's most represented themes and the way in which they are articulated, on the basis of lexical occurrences and links.

We used IRaMuTeQ 7.2 (http://iramuteq.org/), a computer assisted textual analysis software that allows statistical analyses to be carried out on the corpus of texts segmented by tags identifying variables. It reproduces the classification method described by Reinert [32]: Hierarchical Downward Classification on a table crossing solid forms and text segments.

We first performed a hierarchical cluster analysis, to retrieve the structuring clusters of the corpus, which correspond to the most represented themes. Then, a correspondence factor analysis was carried out to understand corpus' structuring factors. Finally, we monitor the extracted themes' evolution over time, by tracking the most representative words of each cluster for each year.

Data analysis

The corpus was analysed through criteria regarding study's scope (location and application), method (study's temporality, participants' technology exposure, methodological tools, participants) and results (Human Technology Relationship determinants and recommendations' nature). Criteria were coded based on the full publications and using NVIVO 12 (a computer assisted qualitative analysis software). Criteria were used both for descriptive purpose and as a variable for lexical analysis.

Results

Publications summary

In this section, the main results related to publications distribution are presented. Fig. 3 indicates that collected publications are from all continents, with a larger share in North America, Eastern Asia and Europe.

Publications date from 1982 to 2018 (see Fig. 4). We can observe an important increase in the number of documents the last fifteen years (result for 2018 are partial due to the databases search taking place in 2018).

The three most important sources of publications are *Journal of Power Sources*, *Energy Policy* and *International Journal of Hydrogen Energy* which account for most of the publication (see Fig. 5).

Concerning the applications that are dealt with, more than half of the publication cover transport applications (e.g. buses, car etc.), about a third have undetermined applications or do not focus on a specific application, 11% focus on stationary applications (e.g. building heating, autonomous offgrid sensors etc.) and only 1% cover portable applications (e.g. smartphone) (see Fig. 6).

Lexical analysis results: interest for users

This section summarises results from the lexical analysis, regarding how studies are interested in users, in what proportion, and when. The hierarchical cluster analysis' results indicate that our corpus is structured by 6 clusters which classifies 98.68% of the corpus's segments (see Fig. 7). These clusters represent the significantly mentioned themes in the corpus. They are grouped in three main categories: Technology Deployment, Energy and Human Technology Relationship; representing respectively 35.4% for; 27.6% and 37% of the classified lexicon.

As we can see in Table 1, clusters 4 and 3 are linked to characterize a lexicon related to technology deployment:

- Cluster 4 refers to the deployment of technologies on the market.
- Cluster 3 refers to the deployment regulation by states.

Clusters 2 and 1 lexicon are related to energy:

- Cluster 2 refers to the technical aspects of the energy transition.
- Cluster 1 refers to the challenges of the energy transition.

Clusters 5 and 6 are linked to describe a discourse related to the human technology relationship:

- Cluster 6 refers to approaches that aim to understand the relation between users and Hydrogen Energy Systems.
- Cluster 5 refers to approaches that aim at evaluating user's reaction to existing or future Hydrogen Energy Systems.

Fig. 8 shows that the theme of Energy is at first predominant, then slightly decrease over the observed period, while remaining high. The theme of Technology deployment is important throughout the entire observed period and increases to become the major theme from the [1994–1999] period. The theme of human technology relationship starts at the lowest to increase significantly from the [1994–1999]

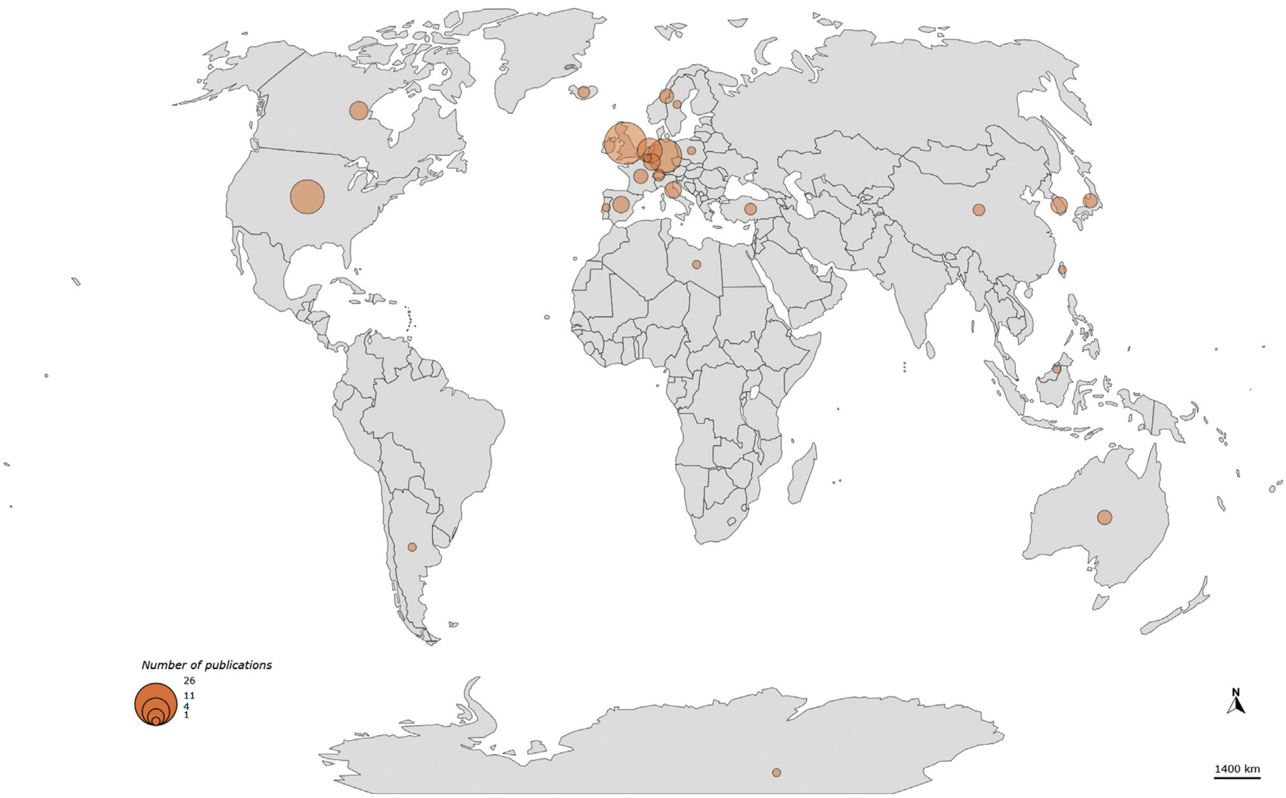

Fig. 3 – Publications geographical distribution.

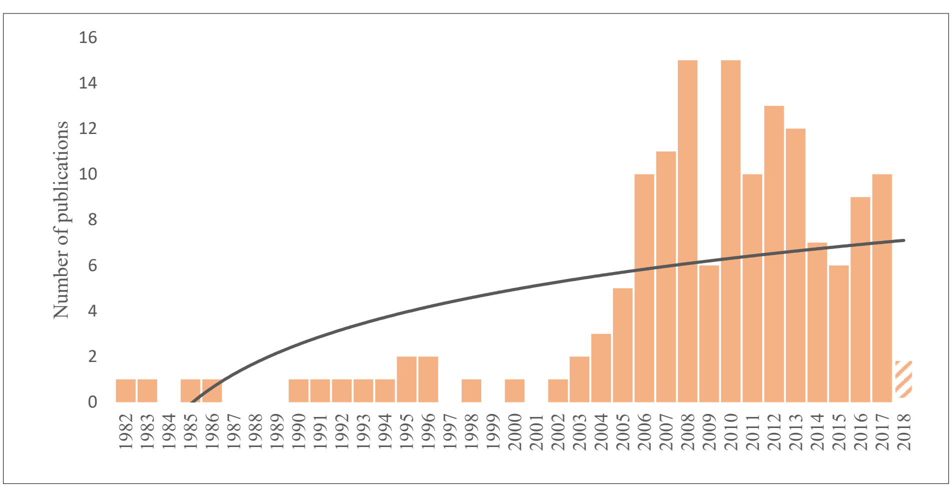

Fig. 4 – Publications distribution through time (partial result for 2018).

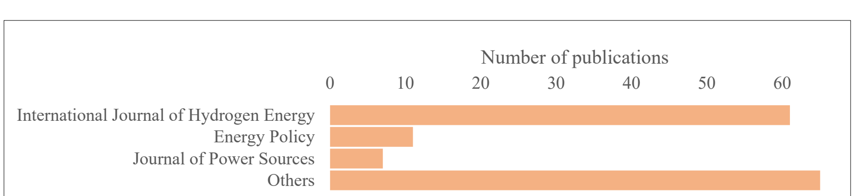

Fig. 5 – Publications main sources.

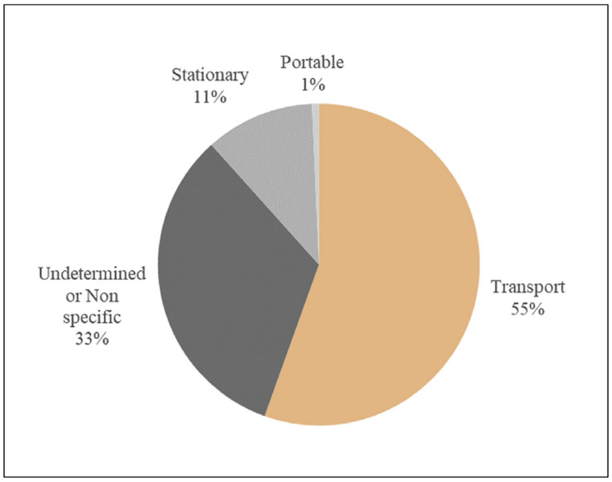

Fig. 6 – Publications applications.

period and to become more important than the Energy theme from [2012–2018].

Studies' methodological approaches

This section presents the methodological approaches that are used to take users into account. Most studies are future oriented (see Fig. 9). That is to say, they focus on technologies that do not yet exist or on future interaction between users and technology. For instance, a study of the probability of a future technology being used, by measuring the intention of use. The small part of the studies that are present oriented, focus on technology demonstrations or already marketed technology (e.g. fuel cell cars).

About half of the studies are empirical (see Fig. 10). Half of these empirical studies were conducted without exposure to hydrogen technologies. The methodological tools used were mainly questionnaires, focus groups and interviews. Public (final users, citizens etc.) were the most implicated participants.

Human technology relationship determinants

A large number of determinants of the Human Technology Relationship quality are identified. They are related to the technology, to the user, to the user and technology interaction, and to the socio-political system (see Fig. 11). The most important of each category are respectively:

Table 1 – Clusters description.

Cluster	Representatives words	Representatives verbatim
Cluster 4: Market	- Market - Fuel cell - Commercialization	*"Hydrogen storage is widely recognized as a critical enabling technology for the successful commercialization and market acceptance of hydrogen powered vehicles."* [39]
Cluster 3: Regulation	- State - Fund - Development	*"state clean energy funds and economic development offices could support and conduct opportunity assessment studies that identify specific fleets, partners and electricity demands."* [40]
Cluster 2: Technical aspects	- Electricity - Power - Density	*"The main conclusions on CO2 full life cycle analysis is that lightduty vehicles using fuel cell propulsion technology are highly dependent on hydrogen production pathway."* [41]
Cluster 1: Challenges	- Energy - Fossil - Security	*"Hydrogen offers a potentially unmatched ability to deliver a de-carbonized energy system."* [42]
Cluster 6: Understand	- Public - Perception - Risk	*"perception of hydrogen energy will be of great importance as we move closer to the implementation of the technologies."* [43]
Cluster 5: Evaluate	- London - Willingness to pay - Resident	*"over one third are clearly in favour of the introduction of hydrogen vehicles in London"* [44]

– **Technology**: technology costs, technology risk and safety, and technology environmental benefits
– **User**: users' environmental concerns, user's knowledge and users' awareness of hydrogen energy
– **User and technology interaction**: technology ease of use, user exposure and familiarity with the technology and user information toward technology
– **Socio-political system**: social influence and norms, social consequences and policy

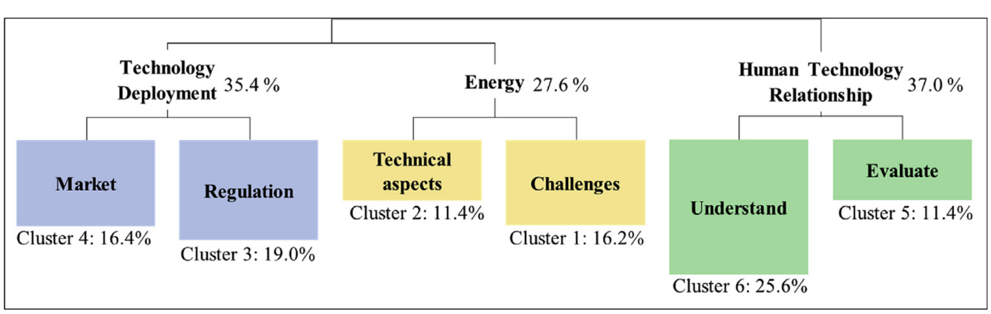

Fig. 7 – Publications hierarchical cluster analysis.

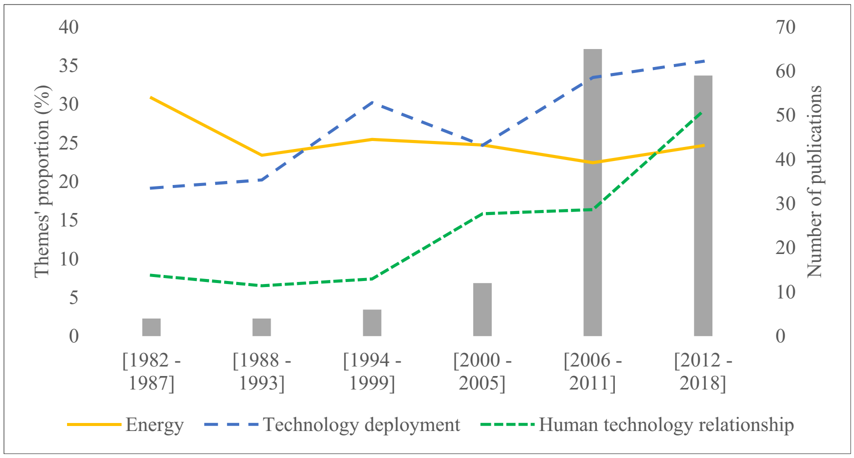

Fig. 8 – Publications themes and number of publications evolution over time.

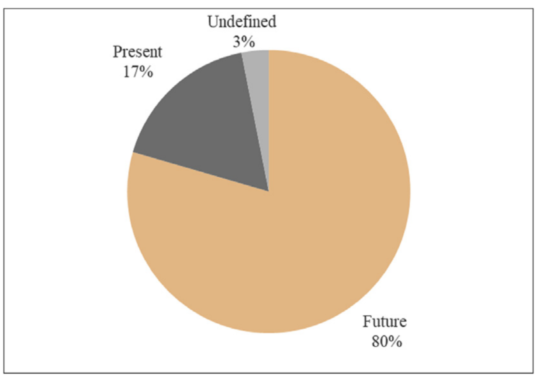

Fig. 9 – Publications' temporality.

Studies' recommendations

Less than half of the studies offer recommendations (see Fig. 12), of which only 13% are design-related (e.g. "some targeted improvements toward the practical utility of the vehicle are needed before market viability is possible, particularly with regard to infrastructure and driving range" [45]), the others being primarily focused on deployment modalities such as communication (e.g. "providing precise risk information will lead to better acceptance" [46]) or policy (e.g. "National policies towards hydrogen should therefore support regional hydrogen strategies and local activities" [47]).

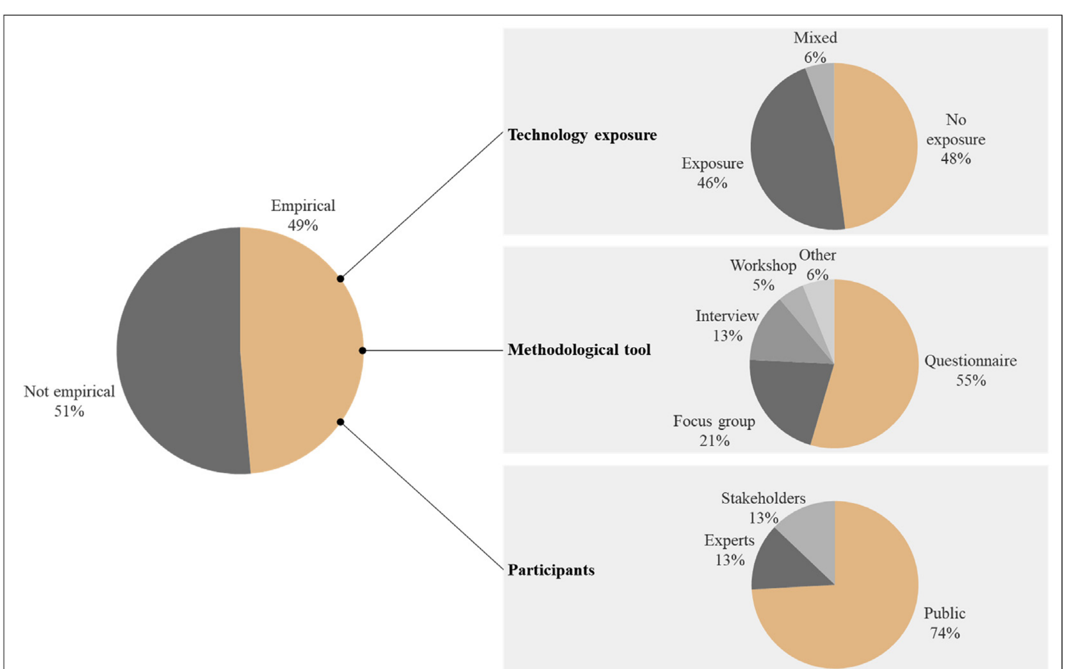

Fig. 10 – Publications technology exposure, methodological tools and participants.

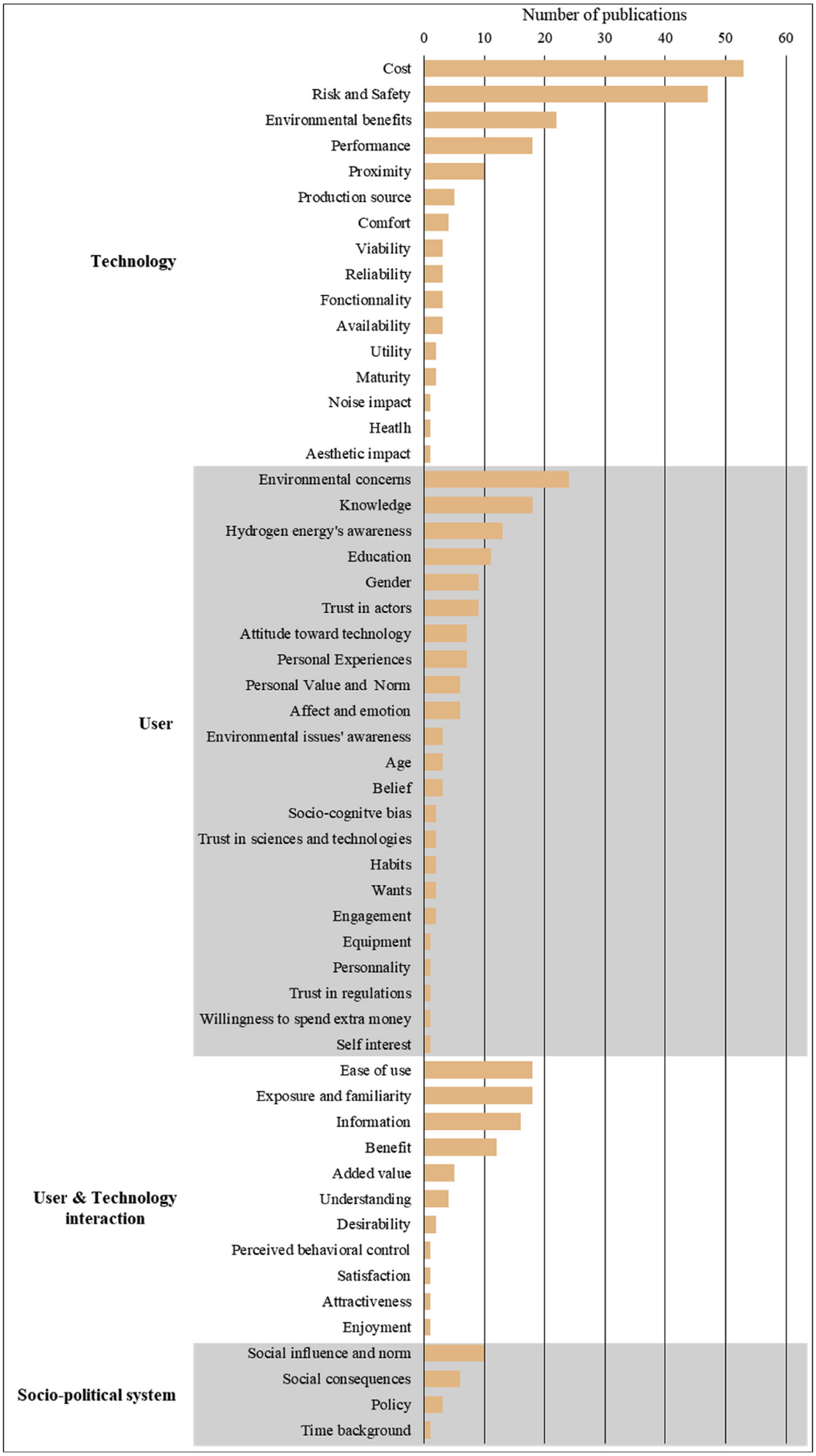

Fig. 11 – Human Technology Relationship determinants identified in the publications.

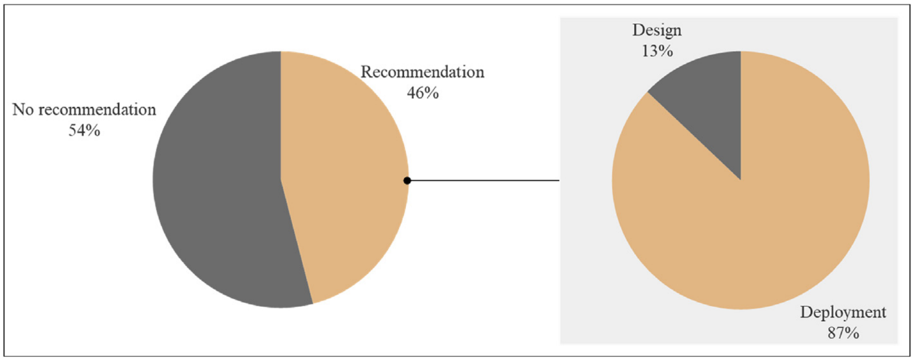

Fig. 12 – Nature of publications' recommendations.

Discussion

End users are crucial in the success of future energy systems. We have shown that they can be taken in account to evaluate a technology acceptability or to feed the design process, and this either upstream or downstream. These approaches are all legitimate and complementary, but when technologies are emergent, the most appropriate approach would be to integrate users as early as possible to feed the design process.

This study allowed us to identify the approaches implemented to take into account users in Hydrogen Energy Systems. Our findings show that the approaches mobilized have mainly the aim of improving technology adoption. Even though users are considered upstream of technology development, they are often perceived as a constraint to the technology (e.g. "Among the possible 'barriers' to such a transition, public attitudes have been identified as an important constraint" [48]). This approach, if necessary, seems insufficient in a context of energy transition which calls for innovation [33]. In addition, many studies focus on understanding users to provide recommendations to facilitate technology acceptance, as these data could be used to enrich the design process. This is consistent with Delzendeh et al. [16]; which indicates that while humans are an important factor in energy systems, they are the least studied factors and most importantly they are not part of the "energy design". To fully benefit from users early understanding to imagine the future alternative-energy systems that will meet expectations of tomorrow's users, users should be considered as a resource and a guide for technology.

Another interesting result concerns the predominance of studies with a focus on transportation application. The stationary applications and especially the building is very little represented, while it is the second highest final energy consumption sector in France, with a significant share of carbonated energy especially for heating [34]. Whereas the political ambitions of the hydrogen deployment plan for France's energy transition predominantly focuses on the uses of hydrogen for industry and transport [35]. In this direction, Scott and Powells [36] in their "social science research agenda for hydrogen transitions", specify that hydrogen is foretell to decarbonize the residential sector, especially heating, and that social researches on hydrogen uses into home is insufficient.

This study also allowed us to synthesize the factors identified in the literature as determining the quality of the Human Technology Relationship. These factors are both specific to the characteristics of the technology and the user, but also to the interaction between them, and finally to the socio-political context in which they are embedded. It is therefore necessary to take into account these different objects of study (human and technology) and level of zoom (individual and socio-political) when designing Hydrogen Energy Systems.

Conclusion

The purpose of this study was to understand how researches have dealt with users in Hydrogen Energy Systems. For this, we carried out a data and lexical analysis of 152 publications related to hydrogen energy final users.

Our results indicate a mobilization of approaches both to understand users and to evaluate users' responses to Hydrogen Energy Systems. However, if nearly all studies are upstream of technologies development, and focus on the future of the Human Technology Relationship, most of the recommendations are not made toward technology design. Thus, it appears that studies tend to follow a techno-centered approach, that support a global technology driver strategy which consists in developing a product, identifying a potential market and then ensuring its acceptance by end users. This is substantial with discourse's change over time that shows a gradual rise of Human Technology Relationship linked terms in the very last periods, which clearly indicates a late consideration for the users.

Given that Hydrogen Energy Systems are emergent [37], we recommend a switch from a technology supportive approach, toward a human-driven approach, for which studies focus on upstream user research, and ambition to propose design related recommendations based on users' understanding. This change in approach would propose not to make a technology or system "desirable", but to design a "desirable" technology or system. We also recommend increasing the share of study which focus on the case of hydrogen energy stationary applications and in particular buildings.

Author contributions

The Corresponding author is A. Martin. A. Martin conducted literature searches and provided summaries of previous research studies. M.F. Agnoletti and E. Brangier participated in the design of the study, provided critical feedback and helped shape the research. M.F. Agnoletti and E. Brangier participated in the financing of the study. A. Martin wrote the protocol, carried out the data collection and the data analysis. A. Martin, M.F. Agnoletti and E. Brangier contributed to the interpretation of the results. A. Martin took the lead in writing the manuscript. M.F. Agnoletti and E. Brangier supervised the whole project. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2020.02.163.

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