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Alternative energy technologies as a cultural endeavor: a case study of hydrogen and fuel cell development in Germany

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Abstract

Background: The wider background to this article is the shift in the energy paradigm from fossil energy sources to renewable sources which should occur in the twenty-first century. This transformation requires the development of alternative energy technologies that enable the deployment of renewable energy sources in transportation, heating, and electricity. Among others, hydrogen and fuel cell technologies have the potential to fulfill this requirement and to contribute to a sustainable and emission-free transport and energy system. However, whether they will ever reach broad societal acceptance will not only depend on technical issues alone. The aim of our study is to reveal the importance of nontechnical issues. Therefore, the article at hand presents a case study of hydrogen and fuel cells in Germany and aims at highlighting the cultural context that affects their development.

Methods: Our results were obtained from a rich pool of data generated in various research projects through more than 30 in-depth interviews, direct observations, and document analyses.

Results: We found that individual and collective actors developed five specific supportive practices which they deploy in five diverse arenas of meaning in order to attach certain values to hydrogen and fuel cell technologies.

Conclusions: Based on the results, we drew more general conclusions and deducted an overall model for the analysis of culture in technological innovations that is outlined at the end of the article. It constitutes our contribution to the interdisciplinary collaboration required for tackling the shift in this energy paradigm.

Keywords: shift in the energy paradigm, hydrogen and fuel cells, culture

Background

Shift in the energy-technology paradigm: from fossil to renewable energies

The contemporary energy system will be radically transformed in the twenty-first century, and these expected changes are often labeled as the ‘new industrial revolution’ [1]. At the core of this revolution is a shift in the energy-technology paradigm away from fossil energy technologies to renewable ones [2]. This paradigm shift is enforced through two pivotal global processes: Firstly, in the future, there will not be enough cheap crude oil for worldwide economic growth [3]. Secondly, it has become almost indisputable that greenhouse gas emissions will lead to considerable changes in global climate. This growing awareness of climate change has strengthened environmental policies and supported the development of renewable energy technologies [4].

Until recently, there has been a huge schism between scientists in their prediction of future oil production. While some of them assumed that oil production has already reached its peak and will soon decline, others argued that there are large undiscovered oil reserves that will be exploited in the future. However, voices supporting the latter position have become scarce, and most scientists now believe that oil production has either already reached its peak and will not increase further [3] or will reach it at the latest by 2035 [5]. Forecasts on worldwide oil demand are even more consistent. Despite the current demand collapse due to the economic crisis,

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it is widely believed that the demand for oil will increase again. Both the decreasing oil production and the growing oil demand will inevitably lead to a rise in oil prices. Hence, economic growth needs to be decoupled from oil, and alternative energy technologies that do not rely on fossil energy sources must be developed.

The second process that promotes this development is climate change. A rise in the global surface temperature has been observed since 1850, when instrumental recording first started [6]. Simultaneously, the concentration of greenhouse gases in the atmosphere has increased since 1750 as a result of human activities, in particular the beginning of the industrialization at the end of the eighteenth century [6]. Though it has been long contested, whether these two processes are related to each other, with some uncertainty still remaining, it is very likely that global warming is caused by humans [6]. Both the concentration of greenhouse gases and the resulting rise in temperature have been characterized by exponential growth since the beginning of the twentieth century. This development has had consequences; scientists have observed several phenomena that are caused by global warming. There is a strong conviction that the rise in temperature resulting from greenhouse gas emissions will lead to considerable changes in the global climate [6,7].

Alternative energy technologies

For all the reasons outlined above, it is necessary to decouple economic growth from fossil energies and to develop alternative energy technologies that rely on renewable energy sources. Hence, the decreasing availability and rising prices of fossil fuels, as well as climate change and its consequences, resulting from their mass usage, not merely cause the change in the energy technological paradigm, but also determine its direction. It is not only a transformation from fossil to non-fossil renewable energy sources, but also a change to those renewable energy sources whose production and consumption allows a CO_2-free energy cycle. Therefore, energy technologies need to be developed, which in combination with renewable energy sources provide a CO_2-free energy cycle from generation to the end use. While this at first glance may seem to be a technical endeavor, the transformation from fossil to renewable energy sources cannot be achieved by engineers alone, as diverse research strands such as, for instance, economic history perspectives (e.g., [8,9]) or microsociological studies (e.g., [10] or [11]) have highlighted the significance of culture in technology development. In fact, interdisciplinary collaboration is required in order to tackle this shift in the energy paradigm.

An important area of application of alternative energy technologies is the transportation sector that heavily relies on the combustion of fossil fuels and thus accounts for a large share of overall emissions. Within the range of this quest for new energy sources, various fuels such as, for example, natural gas, synthetic fuels, or fuels from biomass have been developed and tested in combination with several different propulsion systems in the automotive industry [12]. Hydrogen and fuel cells are among the technologies that open up the chance to deploy renewable energy sources in transportation and electricity, as well as heat generation, in CO_2-free energy cycles. Thus, they target an area which is currently responsible for half of the European Union's [EU] total greenhouse gas emissions [13].

However, for two reasons, this is not necessarily the case. Firstly, the term 'hydrogen and fuel cell technology' suggests a combination of the two technologies, which is possible, but not mandatory. Hydrogen can be used without fuel cells, for instance, as fuel for internal combustion engines in vehicles. Likewise, fuel cells can be powered by fuels other than hydrogen, such as methanol. Furthermore, there is a substantial difference between the two technologies: hydrogen is an energy carrier, while fuel cells are energy converters. Hydrogen and fuel cells are, therefore, the combination of an energy carrier and an energy converter technology. This combination is a broad application area of both technologies, but not the sole one.

Secondly, it should be noted that both technologies are not ecological per se. As hydrogen rarely exists in its pure gaseous form in nature, it has to be obtained from hydrogenous compositions. There are a variety of possible production processes, and hydrogen can be generated from coal, natural gas, biomass, and water. Each production process results in a different energy cycle. Fuel cells present a similar picture. They can be powered by methanol and hydrogen, which can be produced from several different raw materials and in a variety of ways, so that both result in completely different energy cycles.

Therefore, the supporters of hydrogen and fuel cell technologies do not promote them in general, but with regard to their ecological potential. They envisage 'green' hydrogen and fuel cell technologies that rely on renewable energies and contribute to a CO_2-free energy cycle instead of 'black' technologies that are based on fossil energy sources. In order to speak of a CO_2-free energy cycle, the entire fuel process chain has to be considered. This concerns the fuel pathway from 'fuel processing from the primary energy source' to its use 'by the propulsion technology that converts fuel to motion on board the vehicle' [14]. In the case of hydrogen, only hydrogen production from renewable energies can contribute to a CO_2-free energy cycle [14]. This green potential of hydrogen and fuel cell technologies and their wide variety of applications are what attract the interest of many diverse actors. Hydrogen and fuel cells can, for instance, be used to generate power and electricity as well as to run small-scale heating devices for private households and large-scale devices for industry. They can not only provide power for small, portable applications such as mobile phones and notebooks, but can also serve as a propulsion system in large vehicles.

The history of hydrogen and fuel cells

The basic inventions of hydrogen and fuel cell technologies (hydrogen combustion engine and fuel cell) were made at the beginning of the nineteenth century and are today closer to societal usage than ever before. However, the history of hydrogen and fuel cell technologies presents by no means a linear process. Their development for the transport sector is illustrated in detail on the website 'H_2Mobility' of TÜV-SÜD [15], the technical inspectorship for vehicles in southern Germany, and is briefly summarized in the following paragraphs.

The first hydrogen-driven combustion engine was constructed by Issac de Rivaz in 1806. The invention did not receive much attention in the societal discourse for the next 50 years, and it was not until 1863 that the next vehicle driven by a hydrogen-powered combustion engine was constructed by Étienne Lenoir. Nevertheless, the technology has disappeared once again from the scene until the late 1920s when Rudolf Erren constructed a hydrogen-powered two-stroke engine. This development was followed by single concept studies during the following decades, but none of them passed beyond the laboratory stage.

The history of fuel cells is characterized by a similar trajectory. The mechanisms of fuel cell technologies were discovered in 1838 by the German-Swiss chemist Christian Friedrich Schönbein and the British lawyer and natural scientist Sir William Grove, who did research independently of one another. The fuel cell gained its actual name in 1889 from Ludwig Mond and Charles Langer who conducted thorough investigations into this technology. Still, it was not until 1932 that the first model of an alkali electrolyte fuel cell was constructed by Francis Thomas Bacon. This development was followed by the construction of the first vehicle with fuel cell propulsion in 1959.

The development of hydrogen-powered combustion engines and fuel cell propulsion systems exhibited a similar picture until the late 1960s. Both began with basic inventions by a single person, followed by single inventions and wide temporal intervals during which the technologies did not gain societal attention. However, by the end of the 1960s, the initiatives aiming at the societal acceptance of hydrogen and fuel cell technologies started to increase all over the world. This rise in interest was the result of two separate developments: First, hydrogen and fuel technologies were successfully applied in spacecrafts in the 1960s and 1970s where they not only demonstrated their technical functionality, but also gained a high value as key technologies that enabled travel to the moon. Second, the 1973 oil crisis fostered the development of alternative technologies for the transport sector that should decouple modern mobility from crude oil.

Various indicators could clarify the dynamics in the development of hydrogen and fuel cells from the 1970s to the present. One could, for example, take media attention (*cf.* [16-18]) or the number of constructed prototypes and optimistic statements by the industry (*cf.* [19]) as a standard for the upgrading or downgrading of these technologies. However, we decided to focus on the statistics of the German Federal Republic regarding the funding of hydrogen and fuel cells as these illustrate very well the societal and, in particular, the political valuation of these technologies.

Public funding increased continuously from 1974 and reached a temporary peak in 1994 [20]. However, from 1994 onwards, funding decreased and reached its lowest point in 1999 when it fell back to the 1988 level. The end of the lighthouse projects 'HYSOLAR' and 'NECAR' accompanied this development. HYSOLAR, an abbreviation for 'Hydrogen from Solar Energy', was a German-Saudi-Arabian research, development, and demonstration program to assess the chances of CO_2-free hydrogen production from solar energy in Saudi Arabia that then should be transported to Germany [21]. The program ran from 1985 to 1995 without a follow-up project [21]. NECAR, an abbreviation for 'New Electric Car' and 'No Emission Car', was initiated and accomplished by the German car manufacturer Daimler. The objective of this project was to develop a fuel cell propulsion system for vehicles. For this purpose, five fuel cell-powered vehicle prototypes were constructed between 1994 and 2000, when the project had finished.

The end of these projects and the decrease in funding clarify that hydrogen and fuel cell technologies at the turn of the millennium reached the bottom of their history in Germany, but then, a short period from 1999 to 2005 followed in which funding again began to rise and was stabilized at a comparably high level of above €20 million/annum. Thereafter, funding increased vastly, and hydrogen and fuel cell technologies should be funded by at least €100 million/annum from 2008 to 2016 [22], which exceeded the average annual funding from 1974 to 2004 by more than a factor of 10 [20]. This development raises the question: What factors led to this rapid increase in funding in a technology field that appeared to have lost its attraction?

Methods

We chose to conduct a single case study as it allowed the data to be gathered from six different sources:

documents, archival records, interviews, direct observation, participant observation, and physical artifacts [23]. Our information comes from a rich pool of data generated in various research projects on the development of alternative energy technologies. We conducted more than 30 in-depth interviews with experts in this area, attended conferences, analyzed protocols from the meetings of relevant networks, and examined the formation of specific agencies launched to promote the development of hydrogen and fuel cell technologies. Hence, the results presented in this article are drawn from a rich pool of data from multiple sources of evidence in order to increase their validity and reliability [24].

As is usual in case studies, we performed the data collection and analysis simultaneously. After data gathering and analysis, theoretical frameworks which explain the examined phenomenon had to be developed by abstracting the collected information from the case in question [25]. By focusing on principles that regularly occur under certain circumstances, while ignoring aspects that are specific to the case in question [26], we generalized our results into a generic framework that explains how to grasp the cultural influence in technology development.

Results and discussion: hydrogen and fuel cells in Germany from 2000 to 2010

To capture the cultural influences in technology development, Banse and Hauser recommend focusing on the overall context characterized by history, language, and institutions in which the technology is embedded [27]. While the historical dimension has been outlined above, with regard to the language part, it should be noted that in Germany, most attention is paid to transport applications due to the importance of the automotive industry. The transformation of the contemporary CO_2-emitting energy system into a CO_2-free one that is based on hydrogen and fuel cell technologies is strongly associated with the development of a sustainable transport system. The guiding vision is the image of hydrogen that is produced from renewable energy sources and then used as a transport fuel to power fuel cell-driven vehicles.

Institutions, however, do not merely constitute the explainers in this case but are simultaneously part of the explanation as well. The launch and development of the National Organization for Hydrogen and Fuel Cell Technology [NOW], for instance, characterizes a milestone in the history of hydrogen and fuel cells in Germany. On one hand, the launch of the NOW is accompanied by a huge increase in funding and thus constitutes an event that needs to be explained. On the other hand, the NOW influences the further development significantly due to its generous budget. Hence, the launch of the NOW has to be explained in order to understand the important role of this institution in the further proceeding. For this purpose, the relevant individual and collective actors as well as their practices will be portrayed in the following paragraphs as recommended by Banse and Hauser [27].

Individual and collective actors

The trajectory of hydrogen and fuel cell development described above was no coincidence, but rather a result of the work of diverse individual and collective actors. On the basis of our analysis of hydrogen and fuel cell technologies in Germany from 2000 to 2010, we can distinguish at least three types of individual and collective actors: experts, alliances, and agencies.

Experts are individuals who observe the environment for the organizations they belong to. Their objective is to detect relevant changes in good times so that their organizations can adapt to them. Two relevant experts are, for example, Klaus Scheuerer from the German car manufacturer Bayerische Motoren Werke AG [BMW] and Patrick Schnell from the French mineral oil company Total. Scheuerer represents BMW in the agencies 'Transport Energy Strategy' and 'Clean Energy Partnership' [28]. He is the link between BMW and these agencies as he presents the company's efforts in promoting hydrogen and fuel cell technologies to other experts while keeping the company up-to-date on the efforts of other actors. The same can be said for Schnell who does not only represent Total in the Clean Energy Partnership [29], but also represents the Clean Energy Partnership in relation to other agencies such as the National Organization for Hydrogen and Fuel Cell Technology [30].

In order to detect relevant changes at an early stage, experts from diverse organizations work together and exchange their views on the development of certain inventions. This enables the emergence of alliances that stabilize the cooperation. Alliances are 'interorganisational networks' [31] which are composed of experts from diverse organizations. Individuals such as Schnell and Scheuerer compose the hard core of an alliance that initiated several agencies. It consists of 14 persons: 5 from large-scale enterprises, 3 from Federal Ministries, 3 scientists, 2 from associations, and 1 self-employed member. In addition, there exists a group of 25 to 30 associated persons representing the members of the hard core in case of illness or holiday [32]. They cooperate not only to exchange views, but also to influence the development of certain technologies. As this work is quite intense and the individual members of an alliance still have to carry out the daily work for their organizations, they create agencies whose sole objective is to influence the development of specific technologies. Agencies can adopt various organizational forms such as departments, task forces, working groups, partnerships, networks, and so on. In the following paragraphs, the three most influential agencies in Germany should be briefly presented.

The Federal Government represented by the Federal Ministry of Transport, Building and Urban Affairs and the private enterprises Aral, BMW, Daimler, MAN, RWE, Shell, and Volkswagen (TES, unpublished work) launched the Transport Energy Strategy [TES] in May 1998. Ford, General Motors [GM]/Opel, Total, and Vattenfall joined it at a later date [33]. The objective of the TES was to develop a strategy that should secure an internationally leading position for Germany in the field of alternative energies and their production and application in the transport sector during the next 10 years (TES, unpublished work). Out of ten potential alternative fuels and more than 70 different ways to produce them, the involved actors finally identified CO_2-free hydrogen produced from renewable energies as the most promising future fuel (TES, unpublished work) [33].

The Clean Energy Partnership [CEP] is the largest demonstration project for hydrogen and fuel cell technologies in the EU. It was set up in October 2003 [34] and is composed of the car manufacturers BMW, Daimler, Ford, GM/Opel, Honda, and Volkswagen; the energy supplying companies Aral, Linde, Shell, StatoilHydro, Total, and Vattenfall; and the transport companies BVG and Hamburger Hochbahn [35]. Furthermore, the Federal Government is involved in the CEP represented by the Federal Ministry of Transport, Building and Urban Affairs [34]. It funds the project with up to €5 million in order to support the construction of a hydrogen infrastructure [34]. The shared ambition of the involved actors is to work towards a silent and clean transport system with hydrogen and fuel cell technologies at the core [36]. Therefore, they construct hydrogen filling stations and test hydrogen-powered vehicles in order to foster technology development [36].

The NOW was launched in 2008. It is composed of a supervisory board, an advisory board, and a management committee [37]. The supervisory board is composed of representatives from the above-mentioned four Federal Ministries [38]. These ministries are also involved in the advisory board that also consists of representatives from energy suppliers, car manufacturers, and scientific institutions [39]. The main task of the management committee of the NOW is to coordinate and steer all demonstration projects in order to push hydrogen and fuel cell technologies towards market entry [40]. For this reason, the NOW funds more than 35 hydrogen and fuel cell demonstration projects [41]. The most important of these projects is the CEP. From 2008 to 2011, the NOW provided 48% of the CEP's complete budget of €25.8 million [22].

Supportive practices

The actors described above have deployed various practices in order to promote the development of hydrogen and fuel cell technologies. Based on our analysis, we distinguish five practices of (1) networking, (2) agency creation, (3) agenda setting, (4) problem/solution framing, and (5) vision building which will be explained in more detail in the following paragraphs.

Networking refers to the cooperation of the diverse members of an alliance and their efforts to attract new members. This can be done at conferences, workshops, or at other official meetings where alliance members attempt to convince other actors of the value of hydrogen and fuel cell technologies. Very significant events are the so-called parliamentary evenings which are held on a regular basis. These provide diverse actors with the opportunity to meet decision makers from politics, science, and industry and to inform them about the latest developments in hydrogen and fuel cell technologies [42].

Successful networking in alliances is the prerequisite for agency creation. Alliance members create agencies whose sole objective is to enhance the societal usage of certain inventions. Thus, the creation of the agencies aims at accelerating the development of specific technologies. A prime example for the creation of an agency is the emergence of the NOW which was implemented on the initiative of other agencies such as the TES and the CEP in order to set up a superordinate authority that would eventually merge all of them into one central organization. The main task of the NOW is to coordinate and steer all demonstration projects in order to push hydrogen and fuel cell technologies towards market entry [40]. Hence, the launch of the NOW reveals the efforts of diverse actors to make the process of technology development more efficient.

The practice of agency creation can not only result in agenda setting, but can also result from it. Agenda setting focuses on the development, promotion, and implementation of strategies, programs, or plans for the societal usage of a specific invention. The TES is the actor who deployed agenda settings most successfully. It suggested, for instance, the launch of the CEP in June 2001 [43], and the CEP was set up in October 2003 [34]. The TES has also lobbied towards the establishment of a common European platform for the promotion of hydrogen and fuel cell technologies and has apparently succeeded as the launch of the Fuel Cell and Hydrogen Joint Undertaking by the Council of the European Union indicates [44]. Finally, the TES had been successfully lobbying towards the development of a national innovation program for hydrogen and fuel cell technologies and had also succeeded as such a program was initiated by three Federal Ministries in 2006 [20].

Problem/solution framing and vision building are two further practices. Problem/solution framing aims at clarifying that the societal value of hydrogen and fuel cell technologies is based on their capacity to solve serious problems of modern societies. The practice always starts with the presentation of a certain problem that can be of economic, political, or ecological nature. Typical examples of such problems are climate change, rising oil prices, transport sector emissions, or the dependency of Western economies on the import of crude oil. All these issues are portrayed as urgent problems that endanger our standard of living. Hydrogen and fuel cell technologies are then presented as the ideal solution to these problems as they enable an emission-free energy and transport sector on the basis of renewable energies (*cf.* [36,45,46]).

Vision building also refers to the future potential of hydrogen and fuel cell technologies; however, in contrast to problem/solution framing, it does not focus on current problems but rather highlights the advantages of hydrogen and fuel cell technologies by future visions. Vision building is embedding hydrogen and fuel cell technologies in a future world that reflects the current desires for a sustainable and secure energy system. These future visions can bring together diverse actors and coordinate their further actions as they all pursue the same target of realizing the vision. In this way, vision building contributed to successful networking and agency creation, in particular, in the USA, the EU, and partly also in Germany [47].

Arenas of meaning

Actors and their practices do not exhaust the cultural influence in the development of alternative energy technologies. Moreover, the cultural context in which technologies are applied is of great importance as it provides meaning for the use of the technologies [48]. Cultural context does not only provide meaning for technologies, but can also provide a space in which the meaning of a technology is renegotiated and redefined [48]. Hence, diverse individual and collective actors adjust their practices to the cultural context in which they attempt to establish a certain meaning for a specific technology. Considering the development of hydrogen and fuel cell technologies, we identified five dominant arenas of meaning: (1) an economic arena, (2) a political arena, (3) a regional arena, (4) a European arena, and (5) an ecological arena. These five arenas of meaning will be outlined further in the following paragraphs.

The economic arena is characterized by demonstration projects as these shall exemplify the capability and functionality of the technologies and move them closer towards an entry in the market place. Agencies such as the NOW promote the hydrogen and fuel cell technologies as climate-friendly and economically sustainable solutions for the maintenance of modern mobility requirements [22]. Hence, the NOW funds demonstration projects as well as the CEP in order to convince producers and users that 'even today hydrogen-powered cars and busses can be developed as an alternative to conventional road traffic' [22]. Furthermore, it identifies market niches in which fuel cells are already close to market readiness and supports their commercialization with the intention that these niches shall function as stepping stones for the breakthrough into mass markets [22].

The emphasis of the national importance of the technologies depends on the specific implications from the political arena. Here, it is argued that Germany is about to lose its international leadership in hydrogen and fuel technologies if the country does not react immediately [20]. A catchy and often-mentioned slogan is *fuel cells are coming-either from Germany or to it* [49]. This slogan illustrates that Germany could lose about 250,000 jobs if, for example, 20% of all vehicles have to be imported because there is no domestic production of fuel cell cars [20]. Therefore, the development of hydrogen and fuel cell technologies is of national interest and cannot be ignored by politics.

Apart from this political arena, which primarily matters on the national level, we could also identify a regional arena. Here, the ambition is to convince the diverse actors in a specific territorial area of the value of hydrogen and fuel cell technologies by highlighting the special importance of these technologies for the region in question. The agency 'hySOLUTIONS,' for example, focuses on the promotion of hydrogen and fuel cell technologies in the city of Hamburg. Its objective is to turn Hamburg into a hydrogen metropolis and to move the city into a pioneering role in setting international environmental standards [50]. Its regional strategy has apparently been quite successful so far as the 'ZEMSHIPS' project indicates in which diverse industry actors cooperate in order to develop fuel cell ships that enable emission-free trips on Hamburg's rivers [51].

Agencies are also present in the European arena where they promote hydrogen and fuel cells as the key technologies of the future for the EU. The Fuel Cell and Hydrogen Joint Undertaking [52] provides an example of a European agency which is working towards the implementation of the European hydrogen vision [53]. It promotes the hydrogen and fuel cell technologies on the basis of their potential to reduce emissions and to contribute to economic growth. Since its members come from the European Commission, the European industry, and the research community [52], the agency succeeded in involving some of the most influential stakeholders in the EU.

Almost all individuals and collective actors do refer to the ecological potential of hydrogen and fuel cell technologies and support their development in the ecological arena. Diverse studies emphasize the emission reduction potential of the technologies in combination with renewable energies (*cf.* [54,55]). Hydrogen and fuel cells are presented as the key technologies for the transformation of an emission-producing energy system relying on fossil energy sources towards a sustainable emission-free energy system based on renewable energy sources in Germany [20] as well as in Europe [53].

As the illustrations above indicate, these five types of arenas of meaning do not exclude each other but rather overlap and support each other. Diverse actors adjust their practices to the arenas in which they intend to promote the technologies.

Conclusions

The analysis above has revealed how the development of hydrogen and fuel cell technologies is culturally embedded. Individual and collective actors from economy, science, and politics have succeeded in establishing an overall institution for the development of these technologies and to allocate a generous budget for it. Based on these findings, we deducted a general model for the analysis of cultural influences in technological innovations. It focuses on the history of a certain technology and on the actors who promote it with specific practices in specific contexts. The model should be employed for the analysis of the cultural influence in the development of alternative energy technologies in order to contribute to the interdisciplinary collaboration required to tackle the challenges in the energy sector of the twenty-first century.

Our model centers on the process during which diverse actors attempt to portray novel inventions as societally valuable in order to lead them to societal acceptance. It is challenging to find a specific term for the process of 'making something valuable' which is so important for the transformation of inventions into innovations. In German, one could speak of *Wertgebung* or *Inwertsetzung*, but these terms are difficult to translate into other languages and also sound dated. Boris Groys defines valorization in a generic sense as reassessment [56] that can mean both upgrading and downgrading. Unfortunately, this term is neither easy to comprehend nor was Groys the first one to use it. In projects of the European Union, valorization plays a role in applications and evaluations [57]. However, in spite of these ambiguities, valorization still appears to be the most precise term to describe what we intend to analyze. With reference to the work of Boris Groys [56], we define valorization as a reassessment process that transforms inventions into societally valuable innovations.

Analogous to commercialization as the economic transformation of an invention into an innovation, we speak of valorization as the cultural transformation. However, as cultural contexts are only temporary agreements, every valorization process is unique, determined by the invention, the era, and the place. However, despite this uniqueness, a comprehensive framework is recognizable as every valorization process is characterized by certain dynamics that are driven by specific actors who develop special practices in diverse arenas. Therefore, our suggestion is to focus on such dynamics, actors, practices, and arenas that constitute the valorization model outlined in Figure 1.

First, the dynamics of valorization have to be recognized. All valorization processes start with the detection of a value in a specific artifact. We speak of detection in order to emphasize that this value is an inherent aspect of the artifact in question. Hence, value detection is not an ascription process because the value of a certain artifact is present at all times, therefore making it feasible for usage. This feasibility for usage is a necessary but not sufficient condition for the transformation of an invention into an innovation. Archives of technology such as museums, libraries, textbooks, journals, scientific laboratories, movies, patent offices, and so forth are revealing inventions which never became innovations and innovations which were replaced by other ones. They clarify that the detection of a specific value in an artifact does not necessarily lead to its societal usage [58]. Valorization can be successful in the short term but fail in the long term, or it can be interrupted and later successfully resumed; it can occur continuously, discontinuously, or not at all. The dynamics of valorization can be recognized by focusing on factors such as the number of published articles on a specific topic, the amount of funding, or the number of performed demonstration projects. The development of these factors over time indicates whether an invention moves towards societal usage or becomes less relevant.

Actors play a crucial role in the valorization dynamics as they assess whether an invention is only feasible or if it is also worthy of usage. For a successful valorization, there has to be a specific group of actors who believe in the worthiness of an invention and lobby for its societal usage. These valorization actors can be individuals, networks, or organizations. Some of them are working exclusively on the valorization of a specific technology, while others only dedicate a certain part of their daily work to it. What all these diverse types of valorization actors have in common, however, is that they promote the value of a certain invention in order to make other actors aware of it. A successful value promotion results in the upgrading of the invention and can finally lead to its societal usage. The upgrading of an invention, however, also means the downgrading of something else, i.e., the artifact intended to be replaced by the invention or other competing inventions. Hence, valorization actors who promote diverse technologies can be in competition

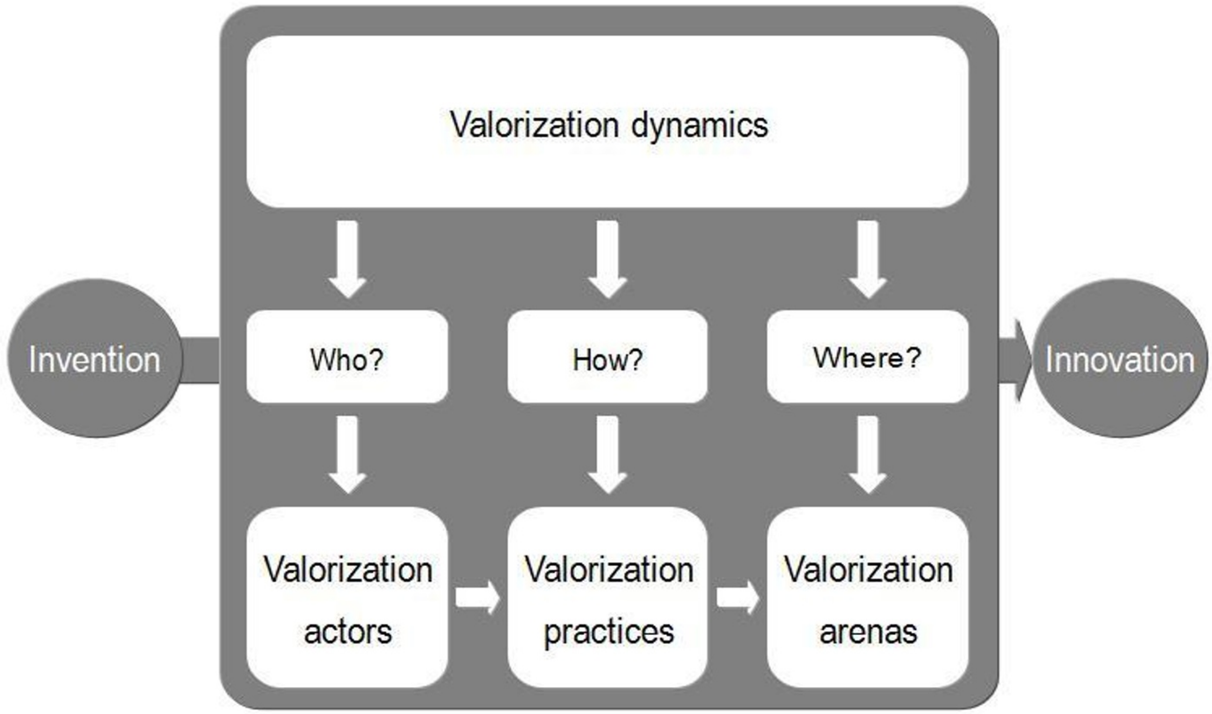

Figure 1 The valorization model.

with each other. However, whether they are in competition depends on whether they regard the inventions as competing or complementary.

In order to promote certain inventions, the actors have to develop diverse valorization practices. They can, for example, cooperate with each other and launch new organizations where their sole objective is to work on the valorization of a specific artifact. In addition, they can lobby for a certain technology on the political or public level. A specific technology can be portrayed as valuable by embedding it in wider societal contexts. It can be illustrated as the ideal solution to certain societal problems or as a desirable goal that could benefit society as a whole. Valorization actors attempt to set the political agenda by such lines of argumentation. Another strategy would be to include the end users in the valorization process. This can be done by public demonstration projects that bring the users in contact with the technology and give them a chance to express their opinion on it. However, the end users can also become the main valorization actors if the artifact in question is made available to them (*cf.* [59]). This occurs, for example, in the case of open source software engineering.

These illustrations have already indicated that valorization practices differ because they are applied in diverse arenas. Valorization arenas denote the topical focus that frames valorization practices. An economic valorization requires other lines of argumentation than a political one. While technologies have to be efficient and low-cost to become attractive for industry, political actors may be more interested in environmentally friendly or societal consequences. Furthermore, it is important whether an invention shall be valorized regionally, nationally, or Europe-wide as these arenas provide different conditions for new technologies. Due to the differences in culture, end user preference, or technical conditions, it may be comparably easy to promote the value of a specific invention in one European country, while it is almost impossible in another. Hence, valorization actors adapt their practices to the arenas which they intend to address.

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Authors' contributions
LM conducted the interviews and collected the data. AG analyzed the general development of alternative energy technologies. Both authors drafted, read, and approved the final manuscript.

Competing interests
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