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Hydrogen Micro-Systems: Households' Preferences and Economic Futility [†]

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Abstract: This study examines the potential market for residential hydrogen systems in light of the trends towards digitalisation and environmental awareness. Based on a survey of 350 participants, the results indicate that although energy experts are sceptical about the benefits of residential hydrogen systems due to their high costs, households are highly interested in this technology. The sample shows a willingness to invest in hydrogen applications, with some households willing to pay an average of 24% more. An economic assessment compared the cost of a residential hydrogen system with conventional domestic energy systems, revealing significant additional costs for potential buyers interested in hydrogen applications.

Keywords: hydrogen; decentralized energy supply; self-consumption; household survey; economic assessment

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1. Introduction

In this extended version of our work, we build upon the findings presented in the previous conference paper [1]. We expand upon the methodology and provide further analysis to delve deeper into the subject matter of residential hydrogen systems. The transition of energy systems involves the growing market participation of consumers who were previously passive. This is achieved through the installation of photovoltaic (PV) systems for decentralized electricity production and the on-site consumption of electricity. The concept of self-production and the consumption of electricity is a subject of debate. Some studies suggest that there are economic inefficiencies [2] and that grid fees may increase [3], while some argue that a more distributed energy generation could bring benefits such as increased security and reliability, as well as reduced power loss at the distributional level [4]. Although there is controversy surrounding self-consumption, studies indicate that households' decisions to invest in a decentralized energy supply is not solely based on economic factors [5]. The potential to contribute to the energy transition and hedge against rising electricity prices is known to trigger a high willingness to invest. This applies not only to PV systems but also to additional energy storage options that increase the potential benefits by storing surplus electricity for later use, thus increasing the amount of self-consumed electricity [6]. Studies show that currently more than 50% of PV systems are installed in combination with a battery [7] even though there is rarely an economic case for the electrical storage [8]. Further, recent global crises may strengthen households' willingness to pay for greater perceived energy independence. The Russian invasion of Ukraine and the subsequent military sanctions and embargoes of Western countries have had a significant impact on the energy markets. The invasion resulted in a significant rise in oil and gas prices, causing increased volatility in the energy markets and many countries responded by taking measures to improve their energy security [9]. In 2022, the year Russia started its invasion of Ukraine, the German Solar Industry Association (BSW) reported record figures for the installation of energy storage systems. The number of installed solar home storage systems in Germany increased by 627,000 units, representing a 52% increase from the previous year [10]. However, batteries are not suitable for long-term electricity storage and are typically used to supply the households with self-produced electricity at night when the sun is not shining. Additionally, the highest demand for electricity occurs during winter months, while most solar electricity is produced in the summer. Therefore, other storage technologies are required to store the electricity produced in summer for later use in winter.

With the development and thus expected cost reduction in hydrogen technologies, they could become an option for seasonal storage in the near future. Some companies have already launched this technological solution to the market, promoting self-sufficiency throughout the year [11]. The technology works as follows: an electrolyser uses excess electricity from the PV system to split water (H_2O) into its components hydrogen (H_2) and oxygen (O_2). Gaseous hydrogen can be stored in pressure tanks with minimal storage loss over time. To generate electricity, hydrogen and oxygen can be converted back to water in a fuel cell. However, this concept has a major drawback—its relatively low efficiency. Currently, electrolysers operate at around 70% efficiency, while the pressurisation of hydrogen for storage has an efficiency of 85–90%. Additionally, fuel cells produce electricity with an efficiency of around 60% [12]. However, their performance may be lower in practice, for example, in degraded use modes. Although, various research is currently being conducted to address these issues [13]. Therefore, the roundtrip efficiency of such residential hydrogen systems is only approximately 35%. It is possible that efficiency may increase with technical development and the recovery of waste heat for residential heating.

The current low efficiency and high costs of residential hydrogen systems do not yet make sense economically. However, it is expected that electricity prices in Germany will remain at a high level in the medium term [14]. Additionally, households have invested in battery storage without a compelling economic case. Therefore, the question arises as to whether households will also adopt hydrogen technologies as seasonal storage for their self-produced electricity.

In this study, we therefore aim to answer the following research questions:

- Is the German population willing to invest in residential hydrogen systems?
- What are their motives?
- Is there an economic case for residential hydrogen systems?
- And finally: What is the potential market for hydrogen home storage systems?

To address these questions, we conducted a market research study and compared the results with those of an economic assessment.

2. Background

2.1. The Perception of Hydrogen and Decentralized Energy Systems

The significance of social acceptance in the adoption of emerging technologies is widely acknowledged. Authors emphasize the role that public perception plays in transition to clean energy [15], both in general and in the context of the hydrogen economy [16]. As a result, studies on the emerging hydrogen economy are increasingly taking into account non-techno-economic factors. One study [17,18] investigated the general public's acceptance of green hydrogen by surveying a total of 2054 citizens. Although hydrogen was familiar to the majority (85%), only a small percentage of the respondents were aware of green hydrogen (21%). Younger people and those with higher education demonstrated a greater level of knowledge. Despite the possible lack of knowledge about green hydrogen, 86% of respondents have a positive attitude towards its use in their own community. Furthermore, 43% of respondents are willing to actively support the local use of green hydrogen. Trust in the processes and actors responsible for its introduction and use is crucial for the success of green hydrogen, in addition to its associated sustainability benefits.

The results indicate that trust in the actors' ability to evaluate the costs and benefits with a view to sustainability and the common good, and to make reasonable decisions regarding technology use, is crucial for advocacy and acceptance. Trust in local political and public administration actors, and in some cases [19], companies, is particularly important in this regard. However, it is evident that while having high trust in science has a positive effect on the general acceptance of the technology, a distrust of companies, and especially large corporations, can negatively impact the acceptance of specific applications [17,18]. The high level of support could also be attributed to the intense debate on the topic at both national and European levels. Key political actors and important stakeholders in the energy system support hydrogen research and see great potential in its production, storage and application. Although key stakeholders recognize the great potential, the general population has limited knowledge about the future applications of green hydrogen. A large proportion of respondents see its primary use in the mobility sector (70%), while only one in two can envision other potential applications, such as for energy supply or in industry.

These findings fit into the general landscape of hydrogen acceptance studies. Among the most important factors influencing societal acceptance of hydrogen technologies identified by studies are prior knowledge and perceived costs or risks and environmental knowledge or education and income [20]. However, the main focus of hydrogen acceptance studies to date has been on the social acceptance of hydrogen in the transport sector [20,21] and the public attitudes to potential changes there. The domestic use of hydrogen, e.g., for cooking or heating, has been little studied and there is still a significant knowledge gap regarding the social dynamics and perceptions of domestic hydrogen heating [22]. A systematic literature review by Emodi et al. [20] in 2021 identified only five articles discussing the use of hydrogen for cooking, space heating and hot water, compared to 28 research studies addressing hydrogen use for transport. In addition, much of the research on domestic use of hydrogen comes from the UK, where hydrogen is envisaged as a potential replacement of gas [23], which is the main method of domestic heating there [24]. As a result, there is little information that can shed light on the social acceptance of residential hydrogen systems of households in Germany. Additionally, it is crucial to highlight the significance of regional differences in perception. Based on experience with renewable energy projects, it is evident that a distinction exists between "general social acceptance" and the "local social acceptance". Location-specific factors, such as trust in local authorities, education and income of residents, are critical considerations [25].

2.2. Hydrogen Usage in Households

A demand for hydrogen in residential neighbourhoods is generally seen for the supply of heat, electricity and mobility.

2.2.1. Hydrogen for Heat Production

At more than 70%, space heating accounts for the largest share of residential energy consumption. A further 14% of energy is used for water heating [26]. Energy demand for space heating has been falling significantly for some years due to energy-efficient renovation and improved thermal insulation in new residential buildings: since 2008, specific final energy consumption (energy consumption per living space) for space heating has fallen by around 10% [27]. If the German government's climate targets are to be met, the energy consumption of the building sector must continue to fall sharply. However, the parallel trend towards more households and larger living spaces tends to lead to higher consumption. In addition, the rate of renovation for existing buildings is well below expectations [28].

Hydrogen is expected to play only a minor role in the supply of heat to residential buildings and neighbourhoods [29]. The demand for heat occurs at relatively low temperature levels, and many alternatives for heat generation are already available for this temperature range. The most efficient of these alternatives is the heat pump. With a coefficient of performance between 2.5 and 5, they are clearly superior to alternative heating systems [30]. (The coefficient of performance COP is the ratio of useful heat gained to the work energy used. For example, a coefficient of performance of 3 means that 3 kWh of useful heat can be obtained from 1 kWh of work energy and 2 kWh of environmental or waste heat. As a rule, the higher the temperature difference between useful heat and cold reservoir, the lower the coefficient of performance of a heat pump.) The heat pumps currently available on the market provide useful heat at a low temperature level. Low flow temperatures are generally most suitable for heating systems in buildings with a relatively high renovation rate. The low renovation rate mentioned above therefore hinders the use of this technology. However, heat pumps with flow temperatures of up to 100 °C are expected in the next few years. The obstacle of the need for renovation could therefore be overcome in the future [31].

Natural gas is currently the most widely used energy source in buildings. The number of natural gas connections has continued to increase in recent years [32]. This could lead to a so-called lock-in effect, as the high initial investment for a gas connection inhibits a switch to more efficient or climate-friendly alternative heating systems in the near future. For households with an existing gas connection, hydrogen is being discussed as a possible energy source for heating. The war in Ukraine has ushered in a new era of energy supply in Germany and Europe, with greater independence from international energy imports. This era is characterized by a renewed political emphasis on the diversification of energy sources and security of supply. This has a direct impact on the market situation for fossil fuels such as oil and gas. In the gas market, Germany and the EU are shifting towards more imports of liquefied natural gas (LNG) from various countries, which will be accompanied by an increase in gas prices until at least until 2030 [33]. This will reduce the relative price difference between gas and hydrogen thus becomes smaller. However, if the existing natural gas network is converted to hydrogen fuel, households will also need to convert their existing gas boilers and pipes.

2.2.2. Hydrogen for Power Production

Approximately 18% of household's final energy demand is met by electricity. This percentage is expected to significantly increase due to the electrification of heat supply (e.g., heat pumps) and mobility (e.g., electric cars). For instance, the purchase of an electric car can cause a household's annual electricity consumption to double and the annual load peaks to even triple [34].

Due to decreasing technology costs for PV systems and additional government incentives, an increasing proportion of private households' electricity demand is being generated and consumed by the households themselves. Currently, the self-consumption of electricity in private households now amounts to over 2 TWh and is continuing to trend upwards [6]. An increasing number of "tenant electricity concepts" involve the use of locally produced electricity by various parties in apartment buildings or neighbourhoods. This trend is expected to be further promoted by additional government measures, such as the photovoltaic obligation in some German states.

To increase the proportion of locally consumed electricity, over half of the installed PV systems are paired with stationary battery storage. This allows surplus electricity generated during sunny midday hours to be used in the evening hours. In addition to the financial benefits of self-supply concepts and hedging against rising electricity prices, households state as part of their motivation that they want to contribute to the energy transition and have a general interest in the technology [6]. Given this context, it would be reasonable to assume that households would also be interested in hydrogen technologies. Decentralized electrolysis can be used to produce hydrogen from surplus electricity during the high-yield summer months and converted back into electricity in fuel cells during the winter months, increasing the ratio of self-supply.

Residential hydrogen applications that are currently in use on a larger scale also utilize fuel cells, although not yet as for improving the self-supply in combination with a PV system. In the early 2010s, over 10,000 residential fuel cells were installed in Japanese homes as combined heat and power systems. These the small-scale systems consist of a fuel cell with a hot water tank, which provide electricity while recovering exhaust heat for the residential hot water supply. An analysis of a demonstration project in an apartment building demonstrated that such a system can cover most of the energy demands of residential homes [35].

In addition to the concept described for the self-supply of neighbourhoods with electricity, there is also an expected demand for hydrogen in the electricity grid of Germany as a whole. This is to ensure power supply and to maintain security of supply. However, an analysis and evaluation of this national hydrogen demand is outside the scope of this study.

2.2.3. Hydrogen for Mobility

In energy balances, the energy demand for mobility is typically attributed to the transport sector rather than households or neighbourhoods. However, the provision of mobility is primarily addressed at a local level in neighbourhoods (e.g., via gas stations) and with the rise of electromobility, even in individual households. In Germany, the transport sector is responsible for just over a quarter of total primary energy consumption, with passenger transport accounting for approximately 63% of energy consumption within this sector. The majority of this energy consumption is attributed to road transport [36]. The EU has recently tightened its CO_2 fleet limits for new passenger cars and light commercial vehicles, meaning that only zero-emission new vehicles will be available on the market from 2035 [37]. Hydrogen-powered cars using fuel cells can still be considered as an option here. However, with the increasing range of electric battery cars, shorter charging times due to high-performance charging technology and the significantly lower efficiency compared to battery vehicles, hydrogen passenger cars have lost their prominence in the discussion, although there are still some challenges associated with the large-scale introduction of electric cars and home charging in particular. The charging of electric vehicles on a daily basis has implications for grid operation and poses challenges for the long-term planning of the electricity infrastructure. In residential contexts, the lack of access to home charging possibilities can be a barrier, particularly for lower-income households, renters and residents of apartment buildings [38]. The National Hydrogen Strategy [39] identifies the most promising areas for direct hydrogen use in combination with fuel cells as medium- and heavy-duty trucks, long-distance coaches and long-distance buses in urban environments. It is not expected for hydrogen refuelling stations to be located in purely residential neighbourhoods, although they may be developed in mixed-use neighbourhoods.

3. The Survey

3.1. Survey Design

The market research survey aimed to estimate the potential market for residential hydrogen systems, taking into account restrictions and acceptance issues that may affect the adoption of these technologies.

To ensure a broad representation of interests within the population, and focus on the most relevant subgroups, we collected survey data from three selected groups: tenants, homeowners with a PV plant and homeowners without a PV plant. The data were collected in December 2020 with the assistance of a market research institute, using an online survey that took approximately 30 min. The final sample consisted of 350 complete datasets (female: n = 168, 48%). The participants were well-balanced in terms of age, with 221 (51%) being over 50 years old, and had a relatively high level of education, with 188 (54%) having completed A-levels. The dataset's structure is presented in Table 1.

To ensure a sufficient and comparable number of participants in each group, the distribution of groups is not representative of these characteristics. Therefore, we weighed our results for living situation and PV ownership according to the distribution in Germany provided by the Federal Statistical Office [40] and a survey on solar energy [41] to obtain results that align with the German population. Note that the numbers in Table 1 do not add up to 100%. The analysis excluded smaller groups, such as apartment owners, due to their low representation in the sample.

Table 1. Sample structure of the quantitative survey.

Group	Tenants [a]	Homeowners [b] without PV	Homeowners [b] with PV
Nb. of participants	106	110	134
Share in survey	30%	31%	38%
Share in population [c]	58%	26%	6.6%

[a] Tenants refers to tenants in apartments as well as houses. [b] Homeowners refers to owners of a single- or double-family house. Owners of apartments or multi-family homes are excluded from the analysis, since the sample was too small. [c] Shares taken from [12,14].

The survey questions addressed the interests and concerns regarding hydrogen applications, including their potential areas of use, the approval of community use concepts and the general openness towards other innovative technologies, such as stationary battery storage. To facilitate a shared comprehension of residential hydrogen systems, survey participants were presented with the illustration displayed in Figure 1 alongside an explanatory text.

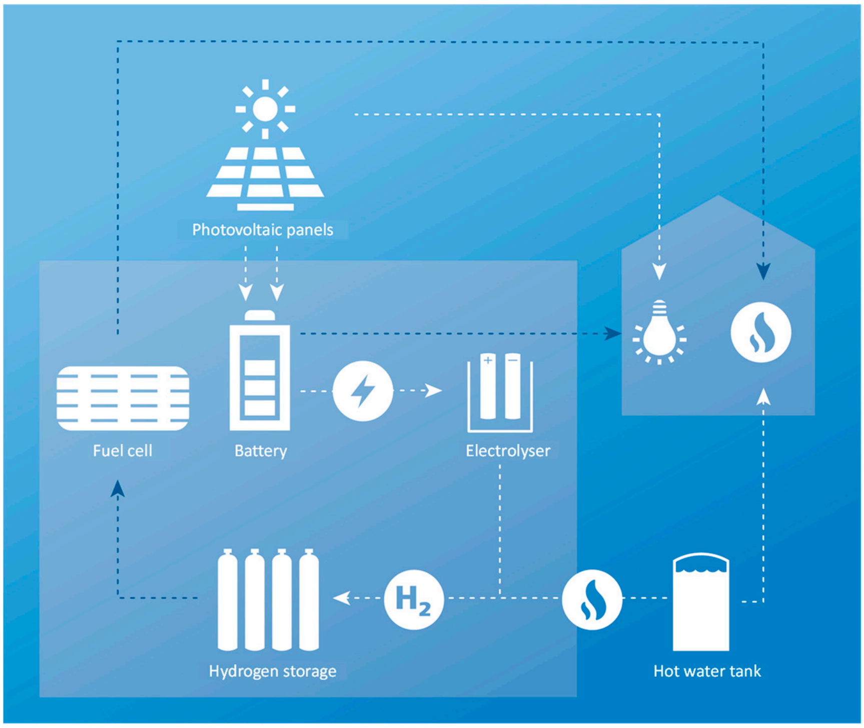

Figure 1. Depiction of the residential hydrogen system shown to the survey participants.

The survey also included questions regarding the willingness to invest in residential hydrogen systems, as well as a question on the willingness to pay more for such technology. The assessment of willingness to invest aims to analyse the potential share of “first-movers” or “innovators”, who are more likely to adopt this innovative technology than the average population and who are more willing to accept certain technical issues that may arise with new technologies.

3.2. Survey Results

3.2.1. Full Sample

The first part analyses the general knowledge of the German population regarding decentralized hydrogen and their attitude towards it (see Table 2). Participants were asked whether they believed hydrogen would play a significant role in the future or if it was just a current hype that would lose its importance. The majority of the sample believed that hydrogen would become more important, while only a small minority believed it would lose importance or was just a hype. However, 17% of the sample (or 19% of the German population) stated that they were unable to give an opinion or had not yet engaged with the topic.

Table 2. Answer to the question "How do you assess the future significance of hydrogen in the society?".

	Will Gain + Likely Gain Importance	Neither	Will Lose + Likely Lose Importance	Do Not Know
Sample	71%	11%	1%	17%
Weighted sample	66%	14%	1%	19%

In the following question, we enquired about the knowledge of residential hydrogen systems. Less than half of the sample and the population had some understanding of the concept and only 4% stated that they had precise idea of the concept (see Table 3). These two questions are crucial for the better interpretation of the results. It is evident that the topic of hydrogen and its technologies are relatively new to a significant portion of the population.

Table 3. Answer to the question "Have you heard before about the possibility of using a hydrogen system (electrolysis + fuel cell) to store the electricity generated by a photovoltaic system in your own home?".

	Pretty Accurate Idea	Rough Idea	No Idea
Sample	6%	39%	55%
Weighted sample	4%	38%	57%

Between the different groups in the survey, i.e., tenants and homeowners, we did not find any significant difference in their knowledge of the technology or their opinion of the future importance of hydrogen in the society. Therefore, the difference between the sample results and the results of the sample weighted according to the three groups is fairly small.

Following the question in Table 3, the participants were shown the explanatory figure and text (see Figure 1). It has to be noted that the figure lacks some consistency for reasons of simplification. Nevertheless, we assume that the figure provides some understanding of the technology to the participants.

The participants were then asked whether they would be prepared to invest in a residential hydrogen system, as shown in the figure. The results (Table 4) show a fairly positive attitude towards the technology.

Table 4. Answer to the question "Would you be ready to invest in the acquisition of a hydrogen system?".

	Yes + More Likely Yes	More Likely No + No	Do Not Know
Sample	54%	29%	17%
Weighted sample	43%	38%	19%

Participants were also asked which applications for the decentral produced hydrogen they would be interested in and were given several options. The answers are as follows: storage for self-produced electricity (56%, weighted sample 50%), heating with hydrogen (47%, weighted sample 45%), filling station for hydrogen cars (24%, and weighted sample 21%), feed-in of hydrogen into the gas distribution system (17%, weighted sample 16%). A total of 29% (weighted sample 40%) stated having no interest in any of the options.

Further, participants were also asked what they feared most about the introduction of a hydrogen system. The most frequently selected concern was that the cost of the technology would be higher than the potential savings (#1), followed by a fear of technical problems (#2) and high maintenance costs (#3).

For the question in Table 4, we found a significant difference between the sample's groups: homeowners and especially homeowners with a PV system are more likely to invest in a hydrogen system compared to homeowners without a PV system ($p \leq 0.001$)

and tenants ($p \leq 0.001$). This is in line with our expectation, as homeowners are also the group for whom the technology is most appropriate, as they own a house and therefore have the option of installing a PV system to produce the electricity for the storage of which the residential hydrogen system is intended. In the following, we will therefore look at the homeowner group in more detail.

3.2.2. Homeowners

As stated above, homeowners with a PV system are most interested in investing in a residential hydrogen system (see Table 5).

Table 5. Answer to the question "Would you be ready to invest in the acquisition of a hydrogen system?" by group.

	Yes + More Likely Yes	**More Likely No + No**	**Do Not Know**
Tenants	38%	42%	21%
Homeowners	49%	36%	15%
Homeowner with PV	70%	14%	16%
Homeowner with PV + Battery	69%	17%	13%

As we assume a link between interest in a battery storage and a hydrogen storage, we also evaluated the investment interest of PV and battery owners as well (N = 52). However, there was no apparent difference between PV owners and PV + battery owners.

When asked about their motives, householders who would invest in a residential hydrogen system stated that they would like to use an innovative product (mean = 4.65), increase the value of their house (mean = 4.47) and contribute to climate protection (mean = 3.43). The respondents indicated the same motives when asked about their interest in investing in battery storage (innovative product ($\text{mean}_{\text{Batt}} = 4.00$), increasing the value of their house ($\text{mean}_{\text{Batt}} = 3.72$), and contributing to climate protection ($\text{mean}_{\text{Batt}} = 3.10$)). We can therefore assume that the markets for home battery systems and residential hydrogen systems overlap.

3.2.3. Innovators

A total of 13% of the sample (N = 39) not only indicated a willingness to invest in a residential hydrogen system but also a willingness to pay more for a hydrogen system compared to conventional electricity and heating systems (on average 24% more). With the stated willingness to pay more, we expected this group to be the first movers in the adoption of decentralised hydrogen systems. In line with Roger's theory on the diffusion of innovations [42], we refer to this group as "innovators".

To better describe this particular group, we used a Gaussian Naïve Bayes Classifier to identify the group's characteristics. Naïve Bayes Classifiers are efficient models for any continuous data. The classifier learns parameters by looking at the statistical values of each feature for each class individually [43]. Using this method, we found that innovators tend to own a PV system and that they differ from non-innovators mainly in their higher trust in energy supply organisations (e.g., grid operators or local/national energy suppliers), in their lower fears related to the use of hydrogen (e.g., raw material use or efficiency) and in their higher affinity for technology (e.g., use of an energy management system or automatic heating control). In addition, the group of innovators is characterized by larger households, higher socio-political engagement and greater concern for environmental issues. In terms of socio-demographic characteristics, higher education, younger age and higher household income were important predictors of innovators. On the basis of these variables, it was possible to predict whether a person was an innovator with an accuracy of 74.7%, 95% CI [61.4%, 87.6%].

Table 6 gives a statistical description of the homeowners in our survey and the group of innovators in comparison with the homeowners in the German population.

Table 6. Descriptive statistics of innovators and homeowners from the survey in comparison with the German population of homeowners.

Mean Values	Unit	Survey		Population
		Innovators	Home-Owners	Home-Owners
PV owners	0/1 dummy	1	0.36	~0.2 [a]
Battery ownership	0/1 dummy	0.49	0.23	NA
Battery ownership or interest	0/1 dummy	1	0.59	NA
HH size	Number	3.2	2.7	2.4 [b]
Avg. age	Number	50	54	58 [c]
Children	0/1 dummy	0.59	0.33	0.21 [b]
Floor size	m^2	171	186	133 [b]
Electr. Consumption	kWh/year	3951	4476	3774 [d]

[a] Survey of German homeowners on solar energy [14]. [b] German Federal Statistical Office [17]. [c] German Federal Statistical Office [17], the average age of the main income earner. [d] The average electricity demand of single-family homes in Germany [18].

Based on these statistics, we estimated that innovators represented around 1 million households, i.e., 8% of the total population of owners of one or two-family houses in Germany (around 14 million).

4. Economic Assessment

As described above, our survey shows a general willingness to invest in hydrogen applications among the respondents and even an average willingness to pay 24% more in “innovator” households. To better understand a potential market for this technology, the willingness to pay needs to be contextualized against the actual potential costs to households. This section looks at the economic viability of a residential hydrogen system and considers the question of its cost-effectiveness compared to conventional solutions.

Few companies have commercialised such technological solutions to the market and there is little comparable information available on the exact costs and potential savings for households. However, to provide an approximate assessment of the cost-effectiveness of a residential hydrogen system, an example is calculated based on data from [11].

The next section compares the costs of a residential hydrogen system consisting of a PV system, a battery, electrolyser and fuel cell with the costs and benefits of a PV system alone and a PV system combined with a battery system. The simulation of a standard household with a PV system over a period of one year provides the starting point for the economic assessment. The load profiles used for the sample household are created according to the guidelines of the Association of German Engineers, as described in guideline 4655 [44]. All scenarios are based on a four-person household (the background to this assumption is that the potential and primary field of application for the use of hydrogen-based home storage systems in Germany is seen in the single-family home segment) with a 10 kW_p PV system in the north-eastern German lowlands, a reference climate region with solar radiation similar to the German average (the reference region consists mostly of the state of Brandenburg, whose mean annual global radiation sum [kWh/m^2] in the period 2011–2020 is closest to the German average according to [45]).

4.1. Baseline Scenario: PV System without Storage System

The hourly irradiance data needed to analyse the solar panel production pattern are taken from the test reference years provided by the German meteorological service [46]. By comparing the solar panel production with household electricity consumption, we can determine the amount of self-consumption. In the baseline scenario, any surplus electricity generated is fed into the public grid, while any additional electricity required is purchased from the grid. The calculations result in electricity costs of around 940 EUR per year for a four-person household as shown in Table 7. Thus, the PV system can save around 1193 EUR per year compared to buying electricity from the grid alone.

Table 7. Results of baseline scenario: PV system without storage system.

Baseline Scenario: PV System							
Month	**Standard Load Profile Total Consumption in kWh**	**Total Production PV System in kWh**	**Consumption Grid Electricity in kWh**	**Surplus Electricity in kWh**	**Monthly Costs Grid Electricity [1] in EUR**	**Feed-in Compensation [2] in EUR**	**Total Electricity Costs in EUR**
January	571.54	206.86	493.96	129.28	157.72	9.18	148.54
February	523.34	285.13	433.32	195.11	138.36	13.85	124.51
March	562.38	693.72	413.38	544.72	131.99	38.68	93.32
April	573.76	1312.2	367.11	1105.54	117.22	78.49	38.72
May	551.01	1582.32	324.37	1355.68	103.57	96.25	7.32
June	527.21	1673.92	295.06	1441.77	94.21	102.37	8.15
July	563.84	1501.73	315.97	1253.86	100.89	89.02	11.87
August	542.99	1288.32	347.23	1092.56	110.87	77.57	33.30
September	557.38	883.78	396.63	723.22	126.64	51.35	75.30
October	559.53	552.27	431.82	424.36	137.88	30.13	107.75
November	555.97	213.24	471.59	128.85	150.58	9.15	141.43
December	595.83	121.92	536.37	62.45	171.26	4.43	166.83
$\sum$	6684.78	10,315.41	4826.81	8457.4	1541.20	600.48	940.73

[1] Electricity costs in Germany were assumed to be 0.3193 EUR/kWh based on 2021 data from Eurostat [47].
[2] Feed-in tariff in Germany for PV systems larger than 10 kW_p was calculated at 0.071 EUR/kWh according to the Renewable Energy Sources Act 2023 [48].

4.1.1. Scenario A: PV System with Battery

In the first scenario a battery with a storage capacity of 20 kWh is added. (A large-scale energy storage system was deliberately chosen here in order to establish comparability with the ambitions of the customer groups in the hydrogen scenario to maximize the utilization of surplus energy from their PV for their own consumption.) The operation of the battery system as an intermediate storage and the self-consumption of the PV system are simulated on an hourly basis. The battery is assumed to have an efficiency of $\mu_{batt} = 90\%$ [49,50]. Table 8 shows the results of the simulation including the resulting costs for a household. The additional battery can save a household approximately 660 EUR in electricity costs compared to the baseline scenario.

Table 8. Results of Scenario A: PV System + Battery.

Scenario A: PV System with Battery							
Month	**Standard Load Profile Total Consumption in kWh**	**Total Production PV System in kWh**	**Consumption Grid Electricity in kWh**	**Surplus Electricity in kWh**	**Monthly Costs Grid Electricity [1] in EUR**	**Feed-in Compensation [2] in EUR**	**Monthly Costs Grid Electricity in EUR**
January	571.54	206.86	377.36	-	120.49 EUR	-	120.49
February	523.34	285.13	283.66	19.84	90.57 EUR	1.41	89.16
March	562.38	693.72	154.53	253.85	49.34 EUR	18.02	31.32
April	573.76	1312.2	60.52	775.71	19.32 EUR	55.08	−35.75
May	551.01	1582.32	44.02	1057.8	14.06 EUR	75.10	−61.05
June	527.21	1673.92	43.9	1156.68	14.02 EUR	82.12	−68.11
July	563.84	1501.73	42.37	958.07	13.53 EUR	68.02	−54.49
August	542.99	1288.32	57.26	784.16	18.28 EUR	55.68	−37.39
September	557.38	883.78	75.26	365.27	24.03 EUR	25.93	−1.90
October	559.53	552.27	121.86	96.84	38.91 EUR	6.88	32.03
November	555.97	213.24	352.93	-	112.69 EUR	-	112.69

Table 8. *Cont.*

Scenario A: PV System with Battery							
Month	**Standard Load Profile Total Consumption in kWh**	**Total Production PV System in kWh**	**Consumption Grid Electricity in kWh**	**Surplus Electricity in kWh**	**Monthly Costs Grid Electricity [1] in EUR**	**Feed-in Compensation [2] in EUR**	**Monthly Costs Grid Electricity in EUR**
December	595.83	121.92	480.16	-	153.32 EUR	-	153.32
∑	6684.78	103,15.41	2093.83	5468.22	668.56	388.24	280.32 EUR

[1] Electricity costs in Germany were assumed to be 0.3193 EUR/kWh based on 2021 data from Eurostat [47].
[2] Feed-in tariff in Germany for PV systems larger than 10 kWp was calculated at 0.071 EUR/kWh according to the Renewable Energy Sources Act 2023 [48].

4.1.2. Scenario B: PV System with Residential Hydrogen System

In the following scenario, we add a residential hydrogen system that includes a 20 kWh battery for the short-term storage and compressed hydrogen gas cylinder bundles that can store the equivalent of 300 kWh of usable electrical energy. The overall efficiency of the hydrogen system is assumed to be 33.69%, with an efficiency factor of 70% for the electrolyser and 55% for the fuel cell according to the manufacturer's specifications [11] as well as an efficiency value of 87.5% for the pressurisation process of the storage according to the literature [12].

For the calculation, the surplus energy from the PV system that remains after the household's demand is met and the battery is fully charged is used in the electrolyser to produce hydrogen as long-term electricity storage. The energy thus fills the hydrogen storage until the maximum hydrogen storage capacity $SOC_{H2,\ max} = 545.45$ kWh is reached. Any additional surplus electricity is fed into the grid. When the PV system and the battery are unable to meet the household's energy demand, the hydrogen is used to generate electricity in the fuel cell, "discharging" the hydrogen storage. Table 9 shows the results of the simulation for the household with the residential hydrogen system. The household can achieve additional savings on its electricity costs of ~73 EUR compared to the PV system with battery scenario and by ~733 EUR compared to the baseline scenario with a PV system only.

Table 9. Scenario B: PV System + Residential Hydrogen System.

Scenario B: PV System + Residential Hydrogen System								
Month	**Surplus Electric-ity in kWh**	**Electricity Demand before [1] in kWh**	**SOC_{H2} in kWh**	**Electricity Demand after [2] in kWh**	**Electricity for Feed-in [3] in kWh**	**Monthly Costs Grid Electricity [4] in EUR**	**Feed-in Compensation [5] in EUR**	**Monthly Costs Grid Electricity in EUR**
January	-	377.36	-	377.36	-	120.49	-	120.49
February	19.84	283.66	12.15	276.98	-	88.44	-	88.44
March	253.85	154.53	155.48	69.01	-	22.04	-	22.04
April	775.71	60.52	475.12	-	-	-	-	-
May	1057.8	44.02	545.45	-	763.33	-	54.20	−54.20
June	1156.68	43.9	545.45	-	1026.01	-	72.85	−72.85
July	958.07	42.37	545.45	-	827.75	-	58.77	−58.77
August	784.16	57.26	545.45	-	658.39	-	46.75	−46.75
September	365.27	75.26	545.45	-	195.30	-	13.87	−13.87
October	96.84	121.86	467.93	-	-	-	-	-
November	-	352.93	246.36	217.43	-	67.43	-	69.43
December	-	480.16	-	480.16	-	153.32	-	153.32
∑	5468.22	2093.83		1403.11	3674.13	448.01	260.86	207.28

[1] Amount of electricity needed to cover a household's consumption after subtracting the PV electricity used and the use of the electricity storage system, but before considering the energy from the hydrogen storage. [2] Amount of electricity needed from public grid after subtracting all storages. [3] After considering the H_2 storage fulfilment. [4] Electricity costs in Germany were assumed to be 0.3193 EUR/kWh based on 2021 data from Eurostat [47]. [5] The feed-in tariff in Germany for PV systems larger than 10 kWp was calculated at 0.071 EUR/kWh according to the Renewable Energy Sources Act 2023 [48].

4.2. Calculation of Total Annual Costs including Investment Costs across All Scenarios

Tables 7–9 showed the potential electricity savings that can be made using a battery and a residential hydrogen system. However, the investment and running costs must also be taken into account when considering the economic viability of a purchase. Table 10 gives an overview of the annual costs of the systems.

Table 10. Comparison annual costs of different storage technologies.

	CapEx in EUR	**Calculated Service Life in Years**	**Annualised CapEx in EUR**	**OpEx in EUR**		**Annual Costs in EUR**
				Annual Electricity Costs	**Maintenance**	
Baseline Scenario: PV System	-- [1]	-- [1]	-- [1]	940	-- [1]	940
Scenario A: PV System + Battery	18,000 [2]	20 [4]	900	280	0 [6]	1180
Scenario B: PV System + Hydrogen Storage System	87,125 [3]	18 [5]	4840	207	499 [7]	5546

[1] Assumed as given across all scenarios. [2] Based on [51]. [3] Based on manufacturer's data [11]. Averaged value including deduction of sales tax on electricity storage systems for private buildings under the federal subsidy in Germany. [4] Based on [49]. [5] Based on value for fuel cell derived from [52]. [6] Based on [53]. [7] Based on manufacturer's data [11].

Table 10 shows, based on the simplified calculation, that the annual cost of a hydrogen storage system is more than 4.5 and almost 6 times higher than the cost of using a battery system or drawing electricity from the public power grid. The calculation shows that the annual electricity costs can be reduced to a minimum with the residential hydrogen system, but the high CapEx has a strong impact on the total cost. Therefore, in a scenario with very high electricity costs, the economic assessment of a residential hydrogen system may become more favourable. The calculation of different electricity price scenarios, shown in Figure 2, indicates that electricity prices as high as 1.57 EUR per kWh would be required to make the residential hydrogen system economically viable compared to the baseline scenario. Compared to Scenario A, including the 20 kWh battery, even much higher electricity prices are needed to make the residential hydrogen system economically viable.

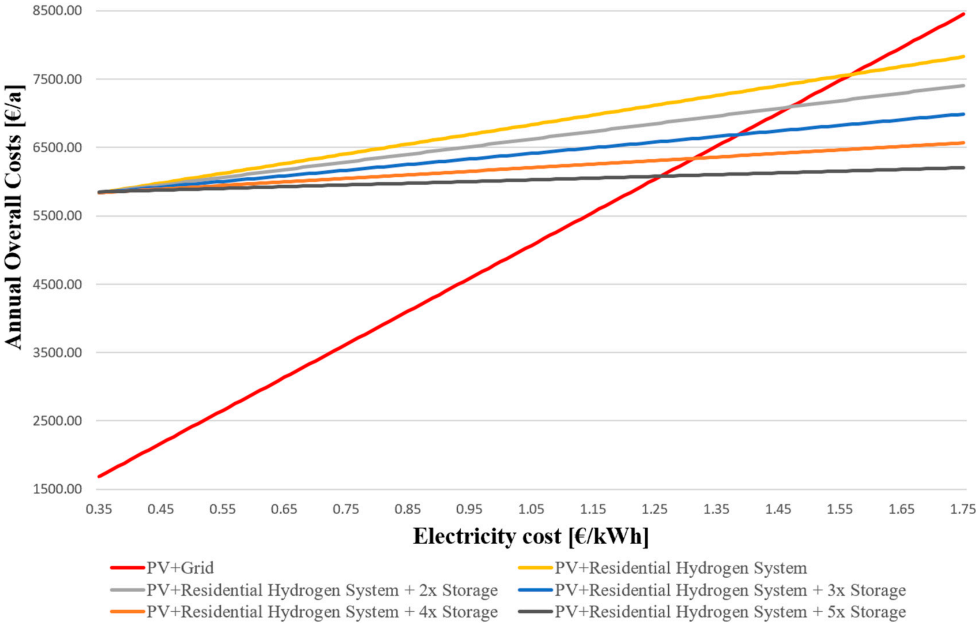

Figure 2. Annual overall costs under different price scenarios.

As an additional factor of influence, the size of the hydrogen storage was analysed. The residential hydrogen system offers the possibility to add additional storage bundles of 545.45 kWh, increasing the storage capacity and therefore the self-consumption of the electricity produced by the PV system. Taking into account the additional cost of the storage bundles, the break-even point for the residential hydrogen system drops to an electricity price of 1.26 EUR per kWh for the scenario with five storage bundles compared to the baseline scenario of grid consumption only.

The hydrogen storage system (when using the electrolyser and fuel cell) can also provide waste heat that can potentially be made available to the household. A recent study [54] suggests that about 8% of the annual heat demand can be met in this way. In the case of a four-person household in Germany, the example used in this paper, with a heat demand of 16,056 kWh [55] and heating costs of 0.0692 EUR/kWh [46], this can result in additional savings of around 89 EUR. Overall, however, the residential hydrogen system is still far from being economically viable, even under very favourable assumptions.

5. Discussion and Conclusions

5.1. Discussion

Our survey shows that the interest in the hydrogen technology is generally high among the German population, although there is a general lack of knowledge and a proportion of around 40% who have no interest in the technology. Thus, answering the questionnaire for this study required a relatively high degree of imagination on the part of the participants. Additionally, some degree of social desirability bias may further have increased the self-reported willingness to pay. We must therefore assume that their stated interest in investing in hydrogen and their preferences for hydrogen may differ significantly from actual investment when there is an established market for residential hydrogen systems.

As the lack of knowledge was anticipated in the design of the questionnaire, we provided an explanatory figure and text for all participants. However, the presentation of the hydrogen system in the survey was only possible in an abbreviated form. Therefore, this explanation would not enable the participants without prior knowledge to answer the questions with the same quality of response as their better-informed peers. In addition, in order to keep the presentation of the hydrogen system short and easy to understand, we had to omit some complex but relevant details, such as the low efficiency of the system. One participant pointed out that she found this form of presentation leading. This must be considered in the context of the sample's relatively positive attitude towards investing in a hydrogen system.

It has to be noted that the survey was conducted in 2020. Given the rapidly evolving nature of technology and attitudes, preferences and awareness might have changed since then. The survey results may not fully capture the current state of knowledge or the current sentiments. Further, the survey was conducted online, which may introduce a bias towards individuals who are more tech-savvy or have access to the internet. This might exclude certain demographics or individuals with different preferences.

Despite the challenges described above, we found that the motives for investing in residential hydrogen systems are the same as for investing in stationary batteries. The target group is also the same, i.e., homeowners with a PV system. Previous studies have found a willingness to pay more for batteries, and 13% of our sample also indicated a willingness to pay more for the hydrogen system. It is therefore possible that an innovative proportion of homeowners will invest in hydrogen systems even though the technology does not (yet) make economic sense.

To put this into context the exemplary economic assessment was carried out to show the extent of the additional costs at this point in time. The results indicate that the high additional costs could still strongly influence the investment decision of the innovative households. The results of the economic assessment have to be seen in the light of some limitations. In particular, the efficiency of the hydrogen system was taken as a fixed value of around 34%. In practice, however, the efficiency would probably be lower, as the electrolyser and fuel cell are not always operated in ideal conditions. In addition, the solar panel production and the intermediate storage of the battery are simulated on an hourly basis, the surplus energy that fills the hydrogen storage tank estimated in the modelling is based on monthly totals. They are therefore subject to inaccuracies compared to actual values under real conditions. An alternative methodology could therefore be to model all values at shorter intervals, e.g., 15 min. However, these limitations do not alter the overall nature of the results.

In the future, further research is needed to provide more evidence on the cost reduction pathways of hydrogen technologies, which could shed a light on the future cost trajectories and the economic viability of technologies such as residential hydrogen systems. There is also much scope for further progress in analysing the framework conditions, applications and drivers for viable business models in the hydrogen economy that will influence future market development. Additionally, decentralised hydrogen systems should be compared with alternative decentralized energy supply systems for a more comprehensive understanding of inefficiencies and the value of long-term storage solutions.

The presented survey and economic assessment were conducted at a single timepoint. Attitudes and perceptions towards hydrogen systems, as well as economics of the systems may vary over time, and a longitudinal study might provide more insights into the dynamics of these preferences.

5.2. Conclusions

In Germany, there is considerable interest in hydrogen technologies, particularly among homeowners who already have a PV system for decentralized electricity generation. Around 1 million households in Germany have been identified as innovators, a group of first movers who have expressed a willingness to pay more for this technology than for conventional electricity supply systems. However, as knowledge of the technology is still relatively limited, the actual willingness to pay may differ and remains to be determined. Nevertheless, there is a strong possibility that hydrogen systems could be adopted because of similar motives for their adoption as home batteries. The objective economic view suggests that residential hydrogen systems are not currently cost effective for homeowners. Even with significant increases in electricity prices, there is still no business case for such systems. Therefore, the high additional costs could strongly influence the investment decision of innovative households. All in all, if costs are significantly reduced in the future, there is potential for the application of residential hydrogen systems.

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