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Green hydrogen as a sustainable operations strategy: A socio-economic perspective

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ABSTRACT

Hydrogen is an energy carrier that can support the development of sustainable and flexible energy systems. However, decarbonization can occur when green sources are used for energy production and appropriate water use is manifested. This work aims to propose a socio-economic analysis of hydrogen production from an integrated wind and electrolysis plant in southern Italy. The estimated production amounts to about 1.8 million kg and the LCOH is calculated to be 3.60 €/kg in the base scenario. Analyses of the alternative scenarios allow us to observe that with a high probability the value ranges between 3.20–4.00 €/kg and that the capacity factor is the factor that most affects the economic results. Social analysis, conducted through an online survey, shows a strong knowledge gap as only 27.5 % claim to know the difference between green and grey hydrogen. There is a slight propensity to install systems near their homes, but this tends to increase due to increased knowledge on the topic. Respondents state sustainable behaviours, and this study suggests that these aspects should also be transformed into the energy choices that are implemented every day. The study suggests information to policy-makers, businesses and citizens as it outlines that green hydrogen is an operations strategy that moves toward sustainable development.

1. Introduction

Overcoming personal selfishness is the greatest obstacle to sustainability, as it is essential to preserving ecosystems and achieving the triple aim of social progress, environmental conservation and economic performance. Of all the sustainable development goals (SDGs), the literature places the greatest emphasis on SDG 13, while an intermediate position is occupied by SDG 7 [1].

The topic of sustainability concerns different perspectives as companies are required to assess business agility [2], but they must also be resilient [3]. Literature gives a great attention to the role of sustainable supply chain [4,5]. Similarly, innovation and policy support play a key role through the carbon tax [6]. However, this is effective when appropriate values are applied to emissions to counter climate change [7]. The energy sector then requires evaluating enabling factors [8] and including consumer opinions [9] aiming to provide insights to decision makers. An organization's choices about the manufacture and distribution of its products make up its operations strategy. The theme operations strategy and renewables requires to be explored in order to take advantage of all the benefits by combining the knowledge of these two distinct topics [10,11].

Renewable energy is linked to the SDGs [12] and green hydrogen is considered an energy carrier that can support the decarbonization of energy systems [13]. Therefore, the different methods of green hydrogen production, their economics, and their environmental impact for all stakeholders need to be determined [14]. However, social factors must also be considered [15]. After describing the background (Section 1.1), we proceed to analyse the literature related to the three dimensions of sustainability for hydrogen: economic (Section 1.2), environmental (Section 1.3), and social (Section 1.4). In light of these studies, research objectives can then be identified (Section 1.5).

1.1. Contextual framework

Using the Scopus database, an analysis of the literature covering the period 2019–2024 was conducted, cross-referencing the keyword "Green hydrogen" with the terms "Economic sustainability", "Environmental sustainability", and "Social sustainability." Figures S1-S3 proposes a co-occurrence network for all papers identified with these criteria. It emerges that the word "sustainable development" is central to all three dimensions and an increasing trend over time is evidenced. Most of the articles in the literature focus on environmental aspects, fol-

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lowed by economic aspects. The social aspect is more neglected but it is still noted that attempts are made to combine the different aspects, including technical and energy aspects. Hydrogen is an energy carrier that can store and provide large amounts of energy while supporting sustainable development [16] and its different production methods can be classified according to the potential and challenges of its components [17]. Electrolysis is one of the main methods for hydrogen generation, in which the passage of electric current through water causes its splitting into oxygen and hydrogen gas [18]. Among renewable sources, many applications emerge with the solar source [19] and with wind power [20] which are characterized by significant global growth in terms of installed power. Applications are emerging that integrate solar energy with retired electric vehicle batteries in order to optimize system reliability and related costs [21]. Therefore, it becomes critical to develop a mathematical model for sizing system components [22] in order to move toward sustainability goals [23]. Indeed while green hydrogen has the potential to reduce carbon emissions and enhance energy security, it is critical to invest in research to reduce the cost of hydrogen production [24]. At the same time, measurable sustainability criteria must be identified to avoid ecological and social injustices with the goal of improving social welfare in planning green hydrogen projects [25]. In this direction, energy communities can be a new social model for ecological transition [26] and hydrogen can also play a key role in this issue [27].

1.2. Economic sustainability of hydrogen

Hydrogen supports carbon neutrality and can provide flexibility to electricity grids based on renewable sources, allowing excess energy to be stored, which can later be used to generate electricity, heat or both, thus contributing to the reduction of greenhouse gas emissions. Within this framework, it is important to analyse the economic impact of green hydrogen in the transportation, industry, and power generation sectors [28]. The use of a sustainable value methodology appears to be useful in assessing the suitability of water sources for electrolysis [29]. Hydrogen production by water electrolysis using proton exchange membranes supports sustainability, with the goal of not only reducing carbon emissions, but there is a need to improve economic feasibility related to electrochemical catalysts and membrane components [30]. Furthermore, a comparison of green hydrogen production by water electrolysis and steam methane reforming shows how co-produced oxygen can be an additional source of revenue to reduce production costs [31]. It is crucial to develop efficient and economical technologies to reduce the overall energy consumption in hydrogen production [32]. Challenges and strategies for green hydrogen production are also addressed through the proposal of hybrid designs that integrate high-temperature technologies with a heliostat solar field. This approach highlights the importance of hydrogen and electricity prices and hydrogen storage capacity for managing peak energy demand [33]. Another important research area is the techno-economic optimization of green hydrogen production using wind energy resources. Challenges related to stability and intermittency in integrating wind plants into power grid systems must be addressed; to do so, site wind potential, equipment costs, and hydrogen load must be considered to determine optimized capacities of wind turbines, electrolyzers, power converters, and storage tanks [34].

1.3. Environmental sustainability of hydrogen

Green hydrogen is proposed as a solution to the growing global energy demand, which is currently met mainly by fossil fuels. Considered a clean and efficient energy carrier, the development of a hydrogen economy is crucial to ensure energy security and future sustainability [35]. Likewise, it contributes to the mitigation of global warming. Analysis of the environmental impacts of different hydrogen production technology configurations shows how they are strongly influenced by electricity and natural gas supply chains [36]. Several approaches can be used to operate hydrogen systems. A significant example of this trend is the analysis of technologies for converting agricultural residues into green hydrogen, promoting a circular bioeconomy model [37]. Further opportunities emerge from methods of producing biohydrogen from algae and cyanobacteria that offer significant environmental benefits [38] and from offshore marine renewables with a focus on issues caused by seawater impurities [39]. Recent advances in the design of advanced electrocatalysts, particularly those based on non-noble metals, aim to make green hydrogen a competitive and sustainable energy source in the global energy landscape [40]. Since hydrogen requires an amount of water, one novel method is direct air electrolysis, which uses a hygroscopic electrolyte to capture water from the atmosphere and produce hydrogen via solar or wind energy [41]. Consequently, the production and use of green hydrogen as a sustainable fuel has several benefits [42].

1.4. Social sustainability of hydrogen

Improving the reliability and social responsibility of the hydrogen supply chain is another key objective. New objective functions aim to maximize the reliability of product delivery and protect the network from disruptions. The inclusion of social factors as a new sustainability indicator is an important step forward in supply chain design [43]. Some authors point out that events and workshops can facilitate social engagement that is fundamental to change management, which includes increased awareness and improved communication among all stakeholders [44]. Some studies focus on analyses conducted through questionnaires. Hydrogen acceptance is based on trust in science, institutions, and the media, and it also emerges that positive and recurring participatory processes and experiences can support the ecological transition [45]. However, other analyses show a knowledge gap with actual knowledge lower than stated and citizens being divided on whether green or grey hydrogen is produced. Acceptance of hydrogen applications varies, with transportation receiving the most support. Suggestions are therefore to narrow the knowledge gap and address concern toward hydrogen safety to mitigate perceived risks [46]. It is critical to develop strategies to support residential decarbonization [47] and some key factors, such as commitment to environmental issues, knowledge of renewable energy technologies, and their potential for action, are critical to the acceptance of hydrogen [48]. Some authors highlight the relevance that the literature will need to have toward the socio-economic aspects of hydrogen use [49].

1.5. Research objectives

Based on the proposed literature, hydrogen is an energy carrier that can support decarbonization. It is destined to play a decisive role in a forward-looking political strategy involving collaboration between Europe and Africa, in accordance with the Mattei Plan, as outlined at the G7 meeting in Borgo Egnazia (Italy) in June 2024 [50]. A gap in the literature emerges on the need to consider the socio-economic dimension of green hydrogen, and this work aims to fill this gap. There are two proposed research objectives (ROs) that will be conducted with reference to the Italian territory:

- RO1 - Calculate the levelized cost of hydrogen (LCOH) of a hydrogen plant obtained from wind power.
- RO2 - Investigating citizens' level of knowledge about hydrogen production through a social analysis based on an online questionnaire.

The information provided, while referring to the Italian context, could be used as a comparison on a more global scale in order to make suggestions for greater dissemination of pragmatic sustainability practices. In addition, it defines or less if green hydrogen can be identified as a sustainable operations strategy.

2. Methodology

This section, in accordance with the two separate ROs, investigates the socio-economic dimension of hydrogen plants related to the social (Section 2.1) and economic (Section 2.2) components.

2.1. Economic model

The discounted cash flow method is used to evaluate the economic viability of a project by estimating future cash flows over the useful life of a project [51,52]. The aim is to calculate the costs that characterize the plant to assess its competitiveness, and for this purpose the LCOH is defined [50,53,54]. This indicator is proposed as the ratio of all total discounted costs, including both the energy production stages from the wind plant and the electrolysis stages, to the total kg produced of hydrogen within the lifetime of the project.

Economic analysis depends on the initial choice on input values, and to overcome this limitation, it is important to analyse alternative case studies. The goal is to give robustness to the indications from the initial scenario. The following analyses are conducted: i) sensitivity analyses assess how individual inputs affect the final result to a greater or lesser degree; ii) scenario analysis, in which several variables are made to vary simultaneously; and iii) risk analysis, which through Monte Carlo simulation, proceeds to a simultaneous variation of critical variables and identifies the probability of having a certain output resulting from 1000 iterations.

Two production plants, each with a specific purpose, are considered for the development of the economic analysis related to the final production of hydrogen:

- An offshore wind plant for renewable energy production;
- An electrolysis plant for the production of hydrogen.

The wind power plant is intended to generate clean energy with the goal of directly powering the electrolysis plant, so as to properly derive green hydrogen. The offshore wind plant is located in southern Italy, a choice derived from ideal environmental conditions for the construction and operation of the plant. Some studies focus on the Apulian territory [55] others on the Sicilian one [56]. Technical data indicate that the wind plant has a total capacity of 30 MW and consists of 6 turbines, each with a capacity of 5 MW. The capacity factor in Italy for offshore wind plants varies between 25 % and 45 %, with peaks reached in specific areas of southern Italy [56]. This analysis considers an intermediate value of this range, setting the capacity factor at 35 %. The annual potential productivity is 91,980 MWh with an annual deterioration of 0.8 %. Regarding the sizing of the electrolysis plant, data from Shell related to a 200 MW electrolysis plant at Tweede Maasvlakte in the Port of Rotterdam are considered. This study considers an 18.5 MW electrolysis plant that will use green energy produced by the wind plant to produce hydrogen. It is estimated that 1776,000 kg of hydrogen is produced in the first year, and again an annual deterioration of 0.8 % is considered. The lifetime of both plants is assessed equal to 25 years. Thus, considering that one year is required to build the plants, it is considered that during year zero the investment costs occur and from year 1 to year 25 the operating costs.

Economic data show that the unit investment costs for the wind power plant turn out to be 2000 €/kW [56], resulting in total investment costs (Capex) of 60,000,000 €. Operating costs (Opex) are set equal to 3 % of Capex costs, which turn out to be 1800,000 € in the first year. With regard to the electrolysis plant, it is decided to locate it directly on land close to the wind power plant in order to avoid transportation costs of the energy produced by the wind power plant itself. The unit cost for the electrolysis plant is 1200 €/kW [31], for a total Capex of 22,200,000 €. Opex, on the other hand, are set equal to 6 % of the Capex costs, which turns out to be 1332,000 € during the first year.

We now proceed to examine additional parameters. Water represents a key resource for the electrolysis process. Some analyses propose that 9 l of water is required for the production of 1 kg of hydrogen [57]. It is expected that in the first year of operation, 15,984 m^3 of water will be used, and the amount will decrease year by year as the plant's productivity deterioration. The cost of water in Italy is considered to be 1.3 €/m^3 [58]. The opportunity cost of capital is assumed to be 6 %. Table 1 presents all input data used in this work. The data are mainly obtained from the literature but their choice is also the result of a comparison with four experts (two academics and two managers) with decades of experience on hydrogen topic.

Table 1
Input data.

Wind power plant	
Total plant power	30 MW
Lifetime	25 years
Unit investment cost	2000 €/kW
Wind turbine cost	10,000,000 €/kW
Capex	60,000,000 €
Opex	3 % Capex
Opex (1st year)	1800,000 €
MW per turbine	5
Number of turbines	6
Production capacity	35 %
Annual productivity (1st year)	91,980 MWh
Annual plant decay	0.8 %
Wind power plant activity days	365
Wind power plant hours of operation	24
Total working hours	8760
Electrolysis plant	
Electrolysis plant power	18.5 MW
Lifetime	25 years
Unit investment cost	1200 €/kW
Capex	22,200,000 €
Opex	6 % Capex
Opex (1st year)	1332 €
Water cost	1.3 €/m^3
Total annual water (1st year)	15,984 m^3
Annual water cost (1st year)	20,779 €
Working days	320
Annual activity hours	2560
Annual productivity (1st year)	1776,000 kg
Annual plant decay	0.8 %

2.2. Online survey

The method of this study is based on a transdisciplinary approach that combines techniques from economics and psychology using a behavioural approach [59]. Specifically, the online survey is the tool employed and is typically used to assess citizens' attitudes toward the hydrogen issue [60,61]. Web-based surveys have advantages but also risks [62] and to mitigate these aspects, several social media platforms (e.g., Instagram, LinkedIn) are used to reach an optimal number of participants. The questionnaire, before being sent out, is submitted to the attention of four experts (coincident with experts used for economic analysis). Suggestions are implemented and it is suggested to compare acceptance towards a hydrogen plant with or without information. Therefore, it is considered useful not to include a description of a hydrogen plant at the beginning of the questionnaire. The questionnaire is distributed via Google Forms and consists of 20 questions divided as follows. The first five questions deal with the characteristics of the sample investigated with demographic information. Next, nine hydrogen-specific questions are proposed that cover different information such as the level of knowledge about hydrogen, acceptance of a system built near one's home, risks, uses and criticality in using water. The set of these questions is interrupted by a description that proposes the difference between grey and green hydrogen to again ask about the acceptance of a plant made near one's home and to delve into the economic perspective in terms of willingness to pay (WTP). We proceed to elaborate on aspects related to wind power since the analysis of this energy source can also

Table 2
LCOH - Baseline scenario.

		Constant Opex	Variable opex
Wind power plant	Total Capex [€]	60,000,000	60,000,000
	Total opex [€]	45,000,000	61,483,975.08
	Energy produced per year [MWh]	91,980	91,980
	Annual deterioration	0.8 %	0.8 %
Electrolysis plant	Total Capex [€]	22,200,000	22,200,000
	Total Opex [€]	33,300,000	45,498,142
	Hydrogen produced annually [kg]	1776,000	1776,000
	Annual deterioration	0.8 %	0.8 %
	Total hydrogen over the 25 years [kg]	40,387,901	40,387,901
Costs	Total discounted costs (wind + electrolysis) [€]	122,533,094	145,317,247
	Energy purchase cost [€/kW]	0.15	0.15
	Opportunity cost	6 %	6 %
LCOH	[€/kg]	3.03	3.60

provide additional information [63,64]. The three questions asked are always about the acceptance to set up a wind power plant near home, the relative WTP to use green sources, and also the evaluation on some characteristics that citizens associate with such plants. Finally, the last three questions concern an analysis on sustainable behaviours useful for framing the habits of the citizens involved in the survey.

The complete questionnaire can be found in the supplementary file. Several questions are examined using a Likert scale (1–5), where 1 indicates not at all agree and 5 indicates absolutely agree. The purpose of the study is described at the beginning of the questionnaire, and the anonymity of the respondents is ensured. Relationships between variables are assessed using descriptive statistics and various analytical methods (e.g. Kruskal-Wallis test, Mann Whitney U test, Chi-Square test, Two Sample T test, One-Way ANOVA).

3. Results and discussion

Similar to the methodology section, the economic (Section 3.1) and social (Section 3.2) results are presented separately here, and a discussion of what has been achieved compared to the existing literature (Section 3.3) is also proposed.

3.1. Economic analysis results

This section aims to propose the results related to RO1 with reference to the methodological content proposed in Section 2.2.

3.1.1. Baseline scenario

The aim is to calculate the LCOH from the economic data for the proposed electrolysis and wind power plants in Table 1. Over the lifetime of the plant, it was observed that the amount of energy generated by the wind plant was not sufficient to meet the needs of the hydrogen production plant. The starting point of the calculation is the assumption that the production of 1 kg of hydrogen requires 51.8 kWh [65] and considering the energy produced by the wind power plant this would have been sufficient for the annual production of 1775,676 kg compared to the projected 1776,000 kg. Energy purchase at the price of 0.15 €/kWh according to Arera data was considered to assess the missing kWh.

Two different models were analysed to calculate LCOH (Table 2). In the first model, where Opex remains constant over time, we have a useful framework for evaluating project performance without considering significant changes in operating costs over time. Analyzing the data, we can see that the sum of the discounted costs of the two plants for the 25-year useful life amount to 122,533,094 €. The annual hydrogen production is expected to be 1776,000 kg, but considering the decay of the plant, the total expected production over the 25 years will be 40,387,901 kg instead of 44,400,000 kg. Their ratio makes it possible to calculate the LCOH value of 3.03 €/kg.

In the second model, we notice a significant difference from the previous model. In this case, Opex grows annually by an inflation rate

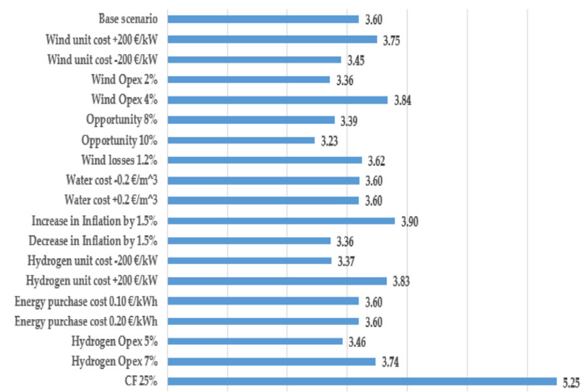

Fig. 1. LCOH (€/kg) - Sensitivity analysis.

of 2.5 % over the previous year. This approach provides a more complete and realistic view of future scenarios, allowing us to assess how cost developments may affect profitability and financial sustainability in the long run. The total discounted costs in this model turn out to be 145,317,247 €, significantly higher than the 122,533,094 € in the model with fixed Opex. Despite the higher costs, the amount of hydrogen produced remains unchanged amounting to 40,387,901 kg for the 25-year useful life. Their ratio allows the LCOH value of 3.60 €/kg to be calculated. In addition, it is appropriate to calculate the Levelized cost of electricity (LCOE) associated with the wind power plant alone, which denotes its competitiveness. LCOE is assumed equal to 39.69 €/MWh and 42.65 €/MWh in the first and second models, respectively. These values are also determined by the size of the plant, which is definitely classified as a large plant.

3.1.2. Alternative case studies - sensitivity analysis

In order to give robustness to the results obtained, alternative case study is considered by evaluating the variations according to critical variables. In particular, attention was paid to the model with time-varying Opex operating costs, a more realistic case study than the one with fixed Opex. Variations in the variables considered, including Opex costs, unit cost of building the two plants, inflation, plant performance losses, Capacity factor, water cost, and power purchase cost, showed differential impacts on the value of LCOH - Fig. 1.

An increase of 200 €/kW in the unit cost of the electrolysis plant raised the LCOH to 3.83 €/kg, a 6.4 % increase over the base case. In contrast, a reduction of 200 €/kW reduced the value of LCOH to 3.37 €/kg. In contrast, an increase of 200 €/kW in the unit cost for the wind plant produced an increase in LCOH to 3.75 €/kg, a 4.2 % increase over the base case, thus being less impactful in the increase in total costs than the change in the unit cost of the electrolysis plant. In fact, a decrease in this cost of 200 €/kW resulted in a LCOH value of 3.45 €/kg,

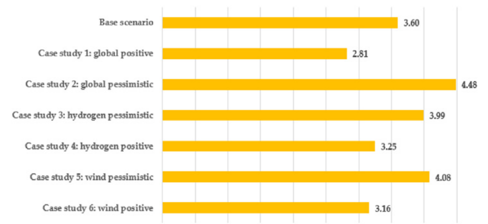

Fig. 2. LCOH (€/kg) - Scenario analysis.

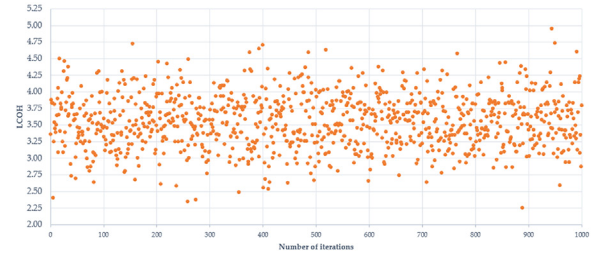

Fig. 3. Risk Analysis – Capacity factor 35 %.

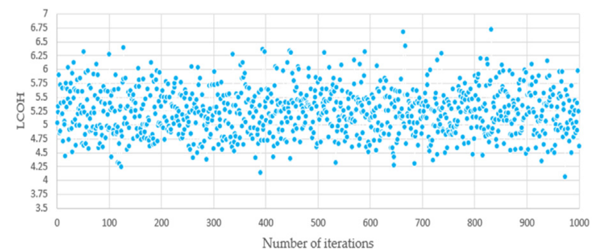

Fig. 4. Risk Analysis - Capacity factor 25 %.

which is higher than the 3.37 €/kg obtained by decreasing the cost of the hydrogen plant. An increase in the opportunity cost to 8 % and 10 %, compared to 6 % in the base case, returned a value of LCOH of 3.39 €/kg and 3.23 €/kg, respectively, highlighting the positive effect of increasing this variable. In the case of changing the LCOH of the wind power plant negatively, bringing it to 1.2 % compared to 0.8 % in the baseline scenario, there are no major deviations from the baseline LCOH value. The levelized costs turn out to be 3.62 €/kg. Changes in the purchase cost of energy showed minor impacts on LCOH. In parallel, changes in the cost of water had a negligible impact, as the related purchase costs are minimal and non-critical to the total project costs. Opex costs for the hydrogen plant are increased and decreased by 1 %. In the positive case, with Opex equal to 5 % of Capex, there is a LCOH value of 3.46 €/kg while in the case with Opex equal to 7 % there is a LCOH value of 3.74 €/kg. The change in Opex related to the wind power plant impacts more on the final LCOH value. In the positive case, with Opex equal to 2 % of Capex, a value of LCOH equal to 3.36 €/kg is reported. In the pessimistic case, with Opex equal to 4 %, there is a LCOH value of 3.84 €/kg. The variable that emerges to be most critical turns out to be the Capacity factor of the wind power plant. A change of this variable in a negative way, from the value of 35 % to the value of 25 %, leads to a huge rise in the value of LCOH bringing it to 5.25 €/kg, an increase of 45.8 %. This is because, making changes to this variable causes a drastic decrease in the energy produced annually by the wind plant, which would no longer be able to provide enough energy for the required kg of hydrogen. In this case study, the energy to be purchased turns out to be significantly more than in the base case, negatively affecting total costs. In Fig. 1, the loss of efficiency of the electrolysis plant at 1.2 % and the increase in Capacity factor by 10 % have not been included because, in these two case studies, the wind power plant considered would produce an excess of energy compared to that needed to produce the required kg of hydrogen. Since this work does not take into account revenues from the sale of any excess energy, this surplus would be wasted, making these case studies uneconomic and with values that differ significantly from those observed with changes in the other variables. Excluding changes to the Capacity factor, the variable that has the greatest impact on the level of LCOH turns out to be inflation. An increase in it by 1.5 %, from 2.5 % to 4 %, raises the index value from 3.60 €/kg in the base case to 3.90 €/kg, representing an increase of 8.3 %. A decrease in this variable leads to an LCOH value of 3.36 €/kg. This result underscores the sensitivity of the LCOH to changes in inflation, highlighting the importance of considering the risks of this variable in financial planning.

3.1.3. Alternative case studies - scenario analysis

In order to consider the simultaneous variation of several variables, scenario analysis was carried out. The variables selected turn out to be only those related to costs for the two production plants. Again, the analysis was based on the model with time-varying Opex costs - Fig. 2. There are six case studies examined: i) case study 1 - global positive; ii) case study 2 - global pessimistic; iii) case study 3 - hydrogen pessimistic; iv) case study 4 - hydrogen positive; v) case study 5 - wind pessimistic; and vi) case study 6 - wind positive. In the global one, the costs of water, electrolysis and wind power plant were included, while in the hydrogen scenario only the cost of electrolysis and in the wind scenario only the cost of the related plant were evaluated. Changes in the variables were considered under both an optimistic and pessimistic scenario:

- 0.2 €/m^3 for water which then varies to 1.1 or 1.5 €/m^3;
- 200 €/kW for the unit cost of the electrolysis plant, which then varies at 1000 and 1400 €/kW;
- 1 % for hydrogen Opex compared to Capex that varies at 5 % and 7 %;
- 200 €/kW for the unit cost of the electrolysis plant, which then varies at 1800 and 2200 €/kW;
- 1 % for the Opex of hydrogen compared to Capex that varies at 2 % and 4 %.

The results show that a simultaneous positive change in the five variables results in a significant reduction in LCOH with a final value of 2.81 €/kg, which corresponds to a 21.9 % decrease compared to the baseline scenario. Similarly, there is a significant increase in LCOH of 4.48 €/kg when these variables increase simultaneously. This 24.4 % increase makes the project less competitive and more financially burdensome. When the cost variables for the two plants are analysed individually, it appears that the energy component has the greatest impact. In fact, for the positive wind scenario the LCOH drops to a value of 3.16 €/kg, a decrease of 12.2 %, while for the positive hydrogen scenario the value drops to 3.25 €/kg, a decrease of 9.7 %. Finally, the pessimistic wind case study reports a LCOH value of 4.08 €/kg, which is higher than the pessimistic hydrogen case study of 3.99 €/kg.

3.1.4. Alternative case studies - risk analysis

For the risk analysis, economic and technical variables only of the model with time-varying Opex were considered, as in previous analyses. This analysis was developed for two case studies (baseline and alternative context), characterized by a Capacity factor of 35 % and 25 %, respectively, which turns out to be a more pessimistic scenario related to the least favourable areas for the installation in Italy of an offshore wind power plant. 1000 iterations were conducted for each of the two models in order to evaluate and understand the potential risks associated with the variation in the value of LCOH in accordance with the literature [50] - Figs. 3 and 4.

Analysis of the results highlights important considerations about the variability and complexity of the context examined. For the scenario with Capacity factor equal to 35 %, 87 % of the LCOH values were found to be in the range of 3.00 €/kg to 4.20 €/kg (base value equal to 3.60 €/kg). However, it is also important to consider cases outside

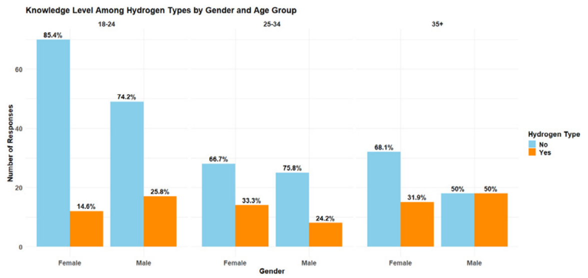

Fig. 5. Level of hydrogen knowledge broken down by age and gender.

these critical ranges, which represent potentially less favourable situations that may require special attention and risk mitigation actions. Narrowing the range with a lower limit of 3.20 €/kg and an upper limit of 4.00 €/kg, we find that 68.6 % of the possible scenarios are within these new critical ranges. Despite the percentage reduction, most of the possible LCOH scenarios still remain within the newly established limits, still indicating a significant probability of achieving the project goals. As for the Capacity factor of 25 % consider us range from its reference value (5.25 €/kg). 88.3 % of the LCOH values are in the range between 4.50 €/kg and 6.00 €/kg. In order to get closer to the baseline value, the lower and upper limits were narrowed to 4.85 €/kg and 5.65 €/kg, respectively, resulting in 64.9 % of LCOH values falling within this new range. Thus, the potential values are well contained within this range. Finally, to compare the two risk analyses, it is noted that for a Capacity factor at 25 % only 1.7 % of the values fall in the 3.00–4.20 €/kg range, confirming how a change in the Capacity factor brings different deviations, even high ones, from the reference scenario.

3.2. Social analysis results

This section aims to propose the results related to RO2 with reference to the methodological content proposed in Section 2.2.

3.2.1. Sample analysis

Our sample is based on 306 participants through an online questionnaire consisting of 21 questions and covers Italian citizens. The questionnaire was distributed through the Google Form platform and shared on various social networks during April 2024. Demographic information shows that the sample is mainly composed of women than men (56 vs. 44 %), and three age groups were identified: "18–24″ (accounting for about half of the sample with 148 responses), "25–34″ (75 responses), and "35+" (83 responses) with an average age of 31.5 years. The responses mainly concern central Italy (47.7 %), but other areas are also represented: North (28.8 %) and South (23.5 %), and for educational qualification, graduates prevail: Middle School Leaving Certificate 1.3 %, High School Diploma 21.9 %, Bachelor's Degree 44.8 %, Master's Degree 24.5 % and Doctorate/Master's Degree 7.5 %. Students make up 51.5 % of the sample, followed by 40 % represented by workers. The sample does not meet the average Italian population but is nonetheless significant and consistent with approaches proposed in the literature [51].

3.2.2. The level of knowledge of hydrogen

The first result that emerges from the social analysis is very significant since only 27.5 % of the sample claims to know the difference between green and grey hydrogen - Fig. 5. People thus turn out to be little or not at all informed about this difference. We can see that men turn out to be more informed about the topic than women (31.9 % vs. 24 %) and differences also emerge at the age level: as the youngest "18–24″ are 19.6 % informed and become 29.3 % for the intermediate "25–34″ group and 38.6 % for the "35+" group. Combining the data by gender and age, it emerges that only in the "man 35+" context are the responses evenly divided, while the lowest value is for "women 18–24." Other interesting data are that the peak of topic knowledge responses for women is in the "25–34″ group, while for this age group is the lowest percentage for men. The sample divided into 6 groups according to gender and age turns out to be statistically significant. In fact, the Chi-Square test gives a p-value of 0.003768.

Analyzing the data by educational qualification shows that those who have a master's degree or hold a doctorate/master's degree are aware of the difference for 34.7 % and 47.8 % respectively. It also shows that the 25–34 bracket that holds a master's degree or doctorate this percentage rises to 60 % and is more than ten percentage points higher than the 35+ bracket.

It was then asked whether green hydrogen could be realized through fossil sources or through renewable sources such as wind power in order to assess consistency with the previous question. The first question has the mean value of 2.20, while the second question has the mean value of 4.03 - Fig. 6. Thus, more knowledge about the topic emerges than previously highlighted but nevertheless a knowledge gap is confirmed for both. The Mann-Whitney test was also performed to compare the distributions of the two groups and $p < 0.0001$, indicating that the observed differences between the two groups are highly significant. Analyzing the participants' responses by gender, for the fossil component the difference between men and women is more significant (2.44 vs 1.90) while there is no great difference for the green component (4.08 vs 3.99). We now turn to an analysis for these two statements based on the distinction by age group. For the grey source statement, we note an average of 2.36 for both the "18–24″ and intermediate "25–34″ age groups, while for the "35+" group we note a lower value of 1.78. For the green source statement, we find an average of 3.89 for the youngest "18–24″ bracket, which increases to 3.99 for "25–34″ and 4.33 for the "35+" bracket. Thus, the older adults turn out to be more aware than the younger ones about how green hydrogen is realized.

For more in-depth analysis, the sample was divided into three different clusters, with regard to gender, a value of 0 was given for men while a value of 1 was given for women; for knowledge of the two types of hydrogen, value 0 represents "no, I don't know the difference" while value 1 represents "yes, I do know the difference" and incorporating questions related to green hydrogen production. It can be seen in Table 3 (Figures A4) that the first cluster consists of 28-year-old women who generally show misinformation about hydrogen. On the other hand, as for the second cluster, this is composed of 27-year-old men and again individuals do not know the difference between the two types of hydrogen. However, greater knowledge is noted than in the previous cluster that green hydrogen cannot be obtained from fossil sources. Finally, the third cluster is composed of older individuals with an average age of 41, with a balanced presence of men and women, although with a slight male predominance. These individuals have a very thorough knowledge about hydrogen as evidenced by the reference questions.

Going into technical detail, citizens were asked whether water was a critical resource for hydrogen (Figures A5). The mean value is 3.5 because one-third of the sample gave a rating of indecision as to what answer to give to this question. Breaking down the figure to demographic level, it appears that men's perception is also more correct than women's in this context (3.62 vs. 3.41) and the same is true for the "35+" sample with a value of 3.63 which is higher than the other two groups (3.51 and 3.36 respectively).

Regarding the uses of hydrogen, 70 % are aware that hydrogen can be used for both domestic, industrial, and transportation uses (Table A1). Although a significant percentage of people are aware of the potential of hydrogen, there is still room for improvement in understanding and disseminating more detailed information on how hydrogen can be used in different areas and what the associated benefits are. Responses for the three specific uses are proposed as follows: 15 % for transportation, 14.5 % for industrial use, and 0.5 % for domestic use.

An intermediate rating is also communicated on the awareness of risks associated with hydrogen plants with an average value of 3 (Figures

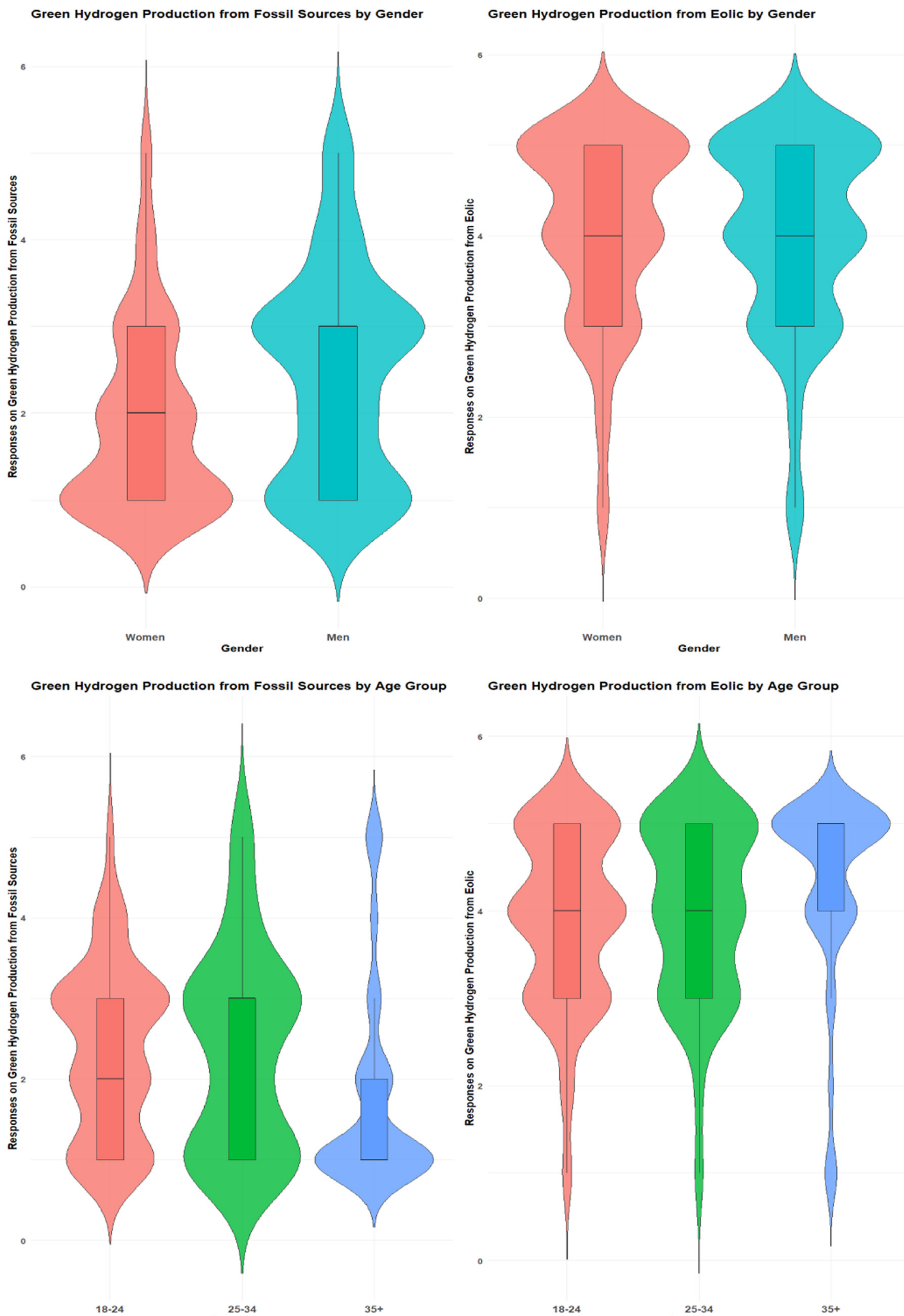

Fig. 6. Hydrogen production from green and fossil sources distinguished by age and gender.

Table 3
Cluster analysis.

Cluster	Average age	Average sex	Average difference types of hydrogen	Media hydrogen green fossil sources	Media hydrogen green wind power
1	28.2	1	0.107	2.79	3.72
2	27.1	0	0.0227	2.19	3.66
3	41.2	0.460	0.782	1.33	4.89

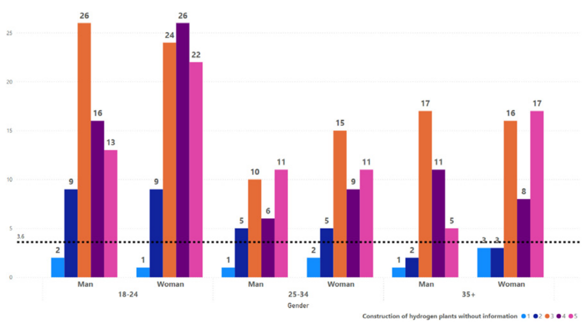

Fig. 7. Hydrogen plant implementation acceptance (without knowledge).

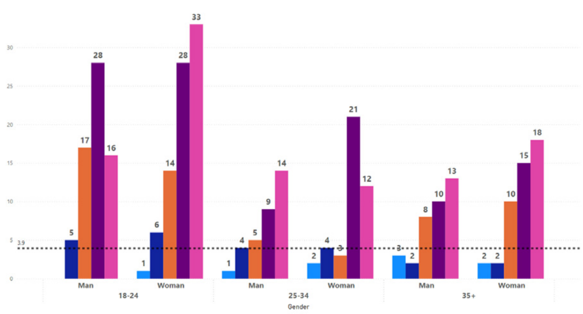

Fig. 8. Acceptance realization of hydrogen plant (with knowledge).

A6). Some risks that hydrogen presents include a high flammability risk, a low minimum ignition energy, and a large deflagration index. The analysis conducted at the age and gender level shows no differences.

3.2.3. Acceptance implementation of hydrogen plants

Citizens typically report a propensity to be sustainable, however, there are often Not in My Back Yard (NIMBY) phenomena in which there is opposition to the establishment of plants near home [66]. A specific question on this aspect was asked at the beginning of the questionnaire and it emerges that one-third of the sample (35.29 %) gave a rating of 3 - Fig. 7. Only 21.94 % completely agreed and the average response was 3.59. Thus, a judgment of indecision emerges, which however tends more toward the "agree" option than the "neither agree nor disagree" option.

After offering the definition in which the difference between green and grey hydrogen is explained, the same question is asked again. In this case, it emerges that 36.27 % gave a score of 4 and 34.64 % a score of 5 with an average value that increased to 3.92 thus denoting less indecision - Fig. 8. It is possible to observe how the information provided, albeit only through a questionnaire, convinced the citizens to greater support for the implementation of the work. However, here we point out the limitation of an online survey that could lead to different results if conducted live.

Table 4 proposes the average responses, broken down by age group and gender, regarding the construction of hydrogen plants before and after providing the definition of green hydrogen and grey hydrogen. The general increase in the average of responses after providing the distinction between the two types of hydrogen is confirmed. Several considerations emerge: i) women are always more likely to agree to the implementation of these plants than men with the exception of the "25–34″ age range; ii) peaks in adherence are recorded for younger women and middle-aged men; and iii) the increase in responses ranges from 0.26 (women 35+) to 0.39 (men 18–24). Table A2 shows a greater propensity of women, while there are minimal differences for the age groups. By pooling the responses for the two types of construction and creating two groups based on sex difference, the Mann Whitney U test reported a p-value of zero. This indicates that the differences in the responses between the two groups are statistically significant. Even when distinguishing the responses for the three different age groups, the Kruskal-Wallis test reports a p-value of zero, confirming previous findings.

Table 4
Hydrogen plant construction acceptance separated by gender and age group.

Age group	Sex	Average Plant construction without knowledge of hydrogen types	Media Plant construction knowing types of hydrogen
18–24	Man	3.44	3.83
18–24	Woman	3.72	4.05
25–34	Man	3.64	3.94
25–34	Woman	3.52	3.88
35+	Man	3.47	3.78
35+	Woman	3.70	3.96

3.2.4. Hydrogen economic outlook

Moving from the technical to the economic sphere, the public was asked how much more they would be willing to pay for green hydrogen compared to grey hydrogen. The responses were analysed by age group and we can see, from the blue line in the graph below, an average value of 10 % - Fig. 9. Different results emerge on age than what has emerged so far: younger people show a higher WTP (11.35 %) than "25–34″ (9.65 %) and "35+" (7.44 %). For younger people we notice longer whiskers, so we can say that the data turn out to be more variable than for the other two groups. The presence of outliers characterizes all the bands. One-Way ANOVA test was performed to compare the WTP among the three different age groups and a $p < 0.01$ emerges, indicating a statistically significant difference. Now analysing the WTP by sex distinction, which although they have two different data distributions, have a similar value: the men's figure is slightly larger (10.02 vs 9.76). As for WTP for men and women, the Two Sample T test reported a p value of 0.8538 and no statistically significant difference emerges between the groups.

3.2.5. Wind power plants

Since green hydrogen is obtained from a wind power plant, the public's perception on this aspect was investigated. The first question, which admitted multiple responses, asked to define the negative effects that characterized this plant, and only 14.4 % of respondents believe that a wind power plant has no negative effects (Table A3). Landscape pollution appears to be significantly impactful to the public, selected by 46.7 %, and this suggests that participants are averse to the modification of their land. In support of this, we note that land value reduction was selected for 24.5 %. Also relevant is noise, selected for 36.3 %. Wind turbines report a range of noise levels between 17 and 39 dB while those of daytime road traffic between 32.5 and 63.5 dB [67]. Furthermore, that study states that noise caused by wind turbines does not cause se-

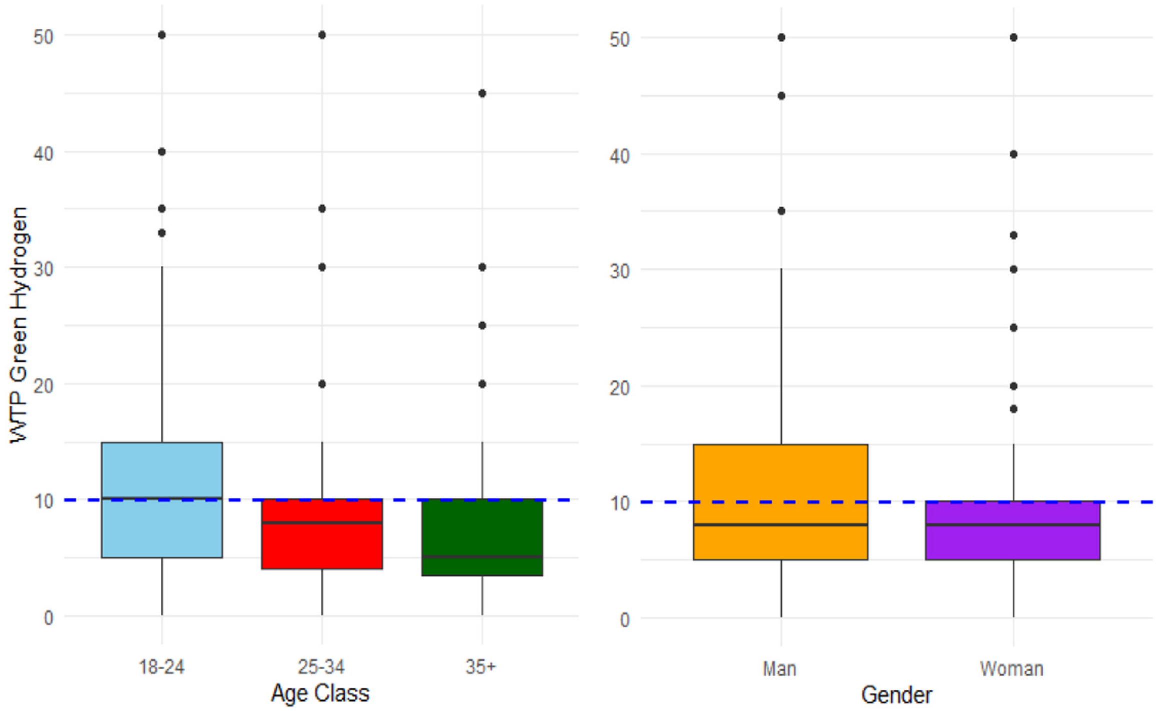

Fig. 9. Willingness to pay for hydrogen plants broken down by age group and gender.

rious symptoms or chronic illness, which can be found in traffic noise, which can cause migraine or headaches, dizziness, impaired hearing, ear pressure, and heart disease. Such aspects thus point to misinformation toward the topic. In addition, the economic aspect associated with costs (12.1 %) and technical aspects such as the presence of shade (11.4 %) or safety related to turbines (11.4 %) do not appear to be impactful. Surprising, however, is the low weight associated with intermittency, which is identified as negative by only 19.3 %.

Although the negative aspects are dominant over the positive ones, there is an average positive leaning toward wind plants. In fact, the question "I favour the construction of wind power plants in the area where I live" has an average value of 3.7 and is thus leaning toward the rating "agree" (Fig. 10). The previous question is perceived as asking to identify and report the negative aspects of wind plants given the content of the question asking to highlight the negative aspects of wind plants. However, if we ask a neutral question such as the one regarding the construction of this type of plant, a different attitude from citizens is identified. The data at the age level sees the "18–24″ group with a value slightly lower than the average (3.6) and a higher value for the "35+" group with 3.9. In addition, women appear to be more likely than men (3.8 vs 3.6). In order to assess the reliability of the data, the Kruskal-Wallis test is proposed for questions related to plant construction (two related to hydrogen and one related to wind power), from which $p < 0.001$ indicating a statistically significant difference between the three groups.

3.2.6. *Wind economic outlook*

Analyzing the WTP for the purchase of wind power, the average value turns out to be 8.68 % (blue line) - Fig. 11. Breaking down the figure by age group, the highest value is recorded for the youngest with 9.82 % and the presence of numerous outliers is evident. The "25–34″ group tends to be more symmetrical and presents 7.79 % preceding the "35+" group with 7.46 %. One-Way ANOVA test was conducted to compare the WTP between the different age groups and the p-value of 0.0624083, indicates that we cannot reject the null hypothesis of no statistically significant differences. Analyzing the WTP for wind energy broken down by gender, we observe an interesting picture, similar to the findings for green hydrogen. The average value for men is slightly higher than for women (8.76 vs 8.62). We show that for women there is a skewed distribution and for men there is greater overall variability. Again the two sample T test was conducted to compare the WTP between the two groups with a p-value of 0.8752 indicating no statistically significant difference.

The younger generation appears to be more inclined to place a higher value on green energy in order to promote its rapid diffusion. However, this inclination seems to be limited to the economic aspect, probably because young Italians, still living mostly in the household, tend to have a reduced perception of the economic value of things. And furthermore, it should be noted that only for WTP did the statistical tools show non-significant differences between the samples examined.

3.2.7. *Sustainable behaviour analysis*

Finally, the social analysis focuses on the behaviour of the selected sample regarding the issue of sustainability. Three questions were asked on a Likert scale of 1 to 5 - Table 5. The first concerns the extent to which respondents avoid buying products from companies that do not respect the environment in their production cycles and records a mean value of 4.07. In general, women are more careful than men, and the highest values are recorded for the older age group with 4.5 and 4.3 for women and men respectively. The second concerns the use of green transportation and there is a higher average value than the previous one of 4.26. There is a similar trend on the breakdown by age and gender, as the more mature age group and the female gender turn out to provide the responses with higher values. Specifically, the highest values are for the "35+" group with 4.6 and 4.3 for women and men, respectively. Finally, the third one concerns the use of reusable products instead of disposable products and here the average value increases reaching 4.39. The behaviour that emerged in the previous two questions that saw women and people in the "35+" bracket being more sustainable is confirmed. Again, the highest values are recorded here and we have 4.6 and 4.3 for women and men, respectively.

It can be seen from these results that women generally adopt better attitudes toward sustainability than men. However, older women and men turn out to be more attentive than younger men, a result that contrasts with what was found for the WTP of renewable energy and green

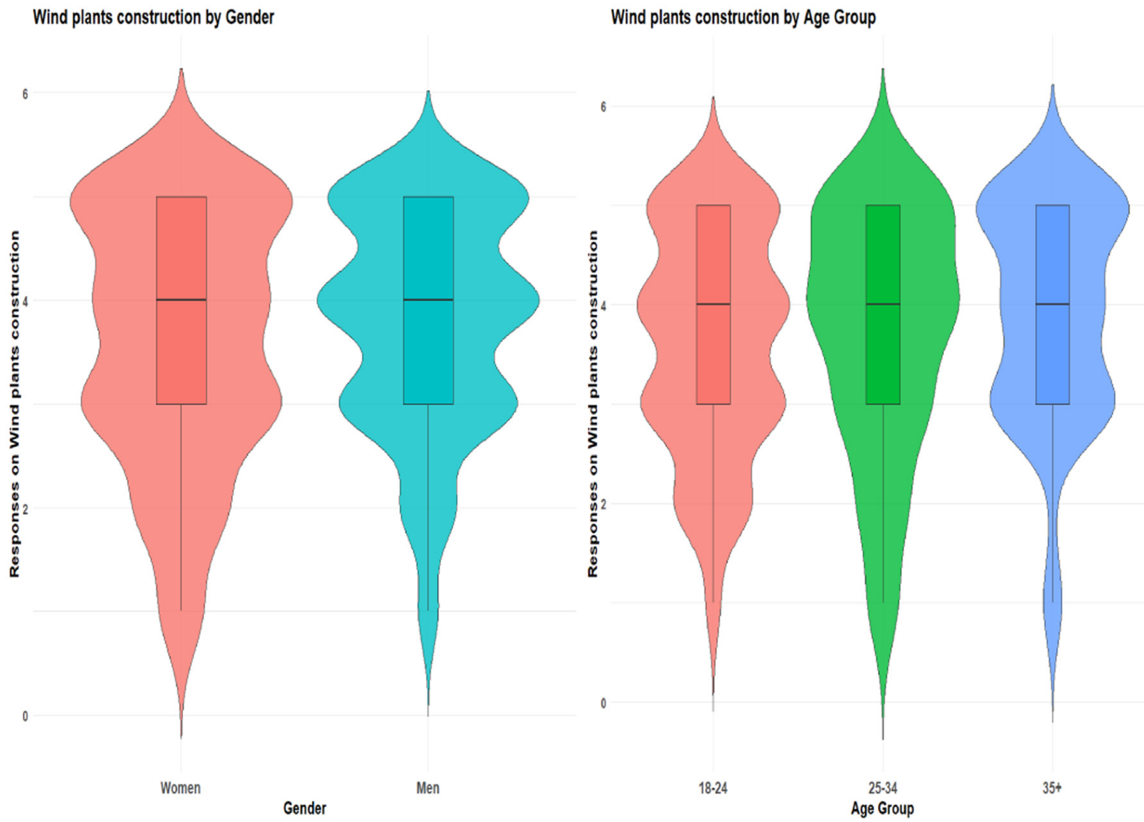

Fig. 10. Acceptance implementation of wind power plants.

Table 5
Analysis of sustainable behaviours.

Age group	Sex	I avoid companies that do not respect the environment	Green transportation	Reusable goods
18–24	Man	3.8	4.1	4.3
18–24	Woman	4.1	4.3	4.4
25–34	Man	3.6	3.9	4.2
25–34	Woman	4.1	4.3	4.4
35+	Man	4.3	4.3	4.3
35+	Woman	4.5	4.6	4.6

hydrogen, where younger men turned out to be more inclined toward sustainability. However, it was noted on these economic data that there is not always statistical significance to support the robustness of the results. On the other hand, with regard to the three questions on sustainability behaviours, the Kruskal-Wallis H test indicated that there was a significant difference in the dependent variable between the different groups, $\chi 2(2) = 20.28$, $p < 0.001$, with a mean rank score of 414.79 for the "respect environment" group, 503.56 for the "reusable goods" group, and 460.15 for the "green transportation" group.

3.3. Discussion

This work proposes new values for both economic and social analysis. Comparing the results obtained with current literature, discordant values with respect to the value of LCOH emerge in some cases. Some previous analyses bring out a value of 3.65 €/kg, very similar to the values of 3.60 and 3.03 €/kg [50]. This deviation, with particular reference to the LCOH value with fixed Opex, is due to the large difference between plant sizes. It is plausible to infer that the divergence in LCOH values is due to the fact that larger plants, with higher final output, benefit from economies of scale. The same aspect is also demonstrated by analyzing the results of other research [68], in which LCOH is 9.29 €/kg for an electrolysis plant producing 200 kg of hydrogen per day. High values are also proposed by other authors, respectively 8.60 and 11.17 €/kg [69]. Hydrogen obtained through polymer electrolyte membranes powered by wind energy and these costs appear to be high because of the costs associated with transportation and the complexity of the supply chain. In contrast, results similar to those obtained in this study those obtained in other research quantifying LCOH as 4.56 €/kg with polymer electrolyte membranes [53]. There are also studies that have a lower value: 2.36 €/kg [70]. It also emerges how the value of LCOH varies by production technology: 7.2–10.1 RMB/kg if obtained using coal, 13.1–19.4 RMB/kg via Carbon Capture and Storage, 16.4–51.8 RMB/kg via electrolysis from renewable energy. If produced by wind or solar energy, LCOH results in 26.63–35.56 RMB/kg (thus about 3.38–4.52 €/kg) and 40.91–51.80 RMB/kg (about 5.20- 6.58 €/kg), respectively [53]. On the other hand, analyzing the electrolyzer technologies used resulted in LCOH of 7.60 €/kg for alkaline water electrolysis technology, 8.55 $/kg for proton exchange membrane electrolysis technology, 10.16 $/kg for solid oxide electrolysis with electric heaters technology, and 7.15 $/kg for solid oxide electrolysis combined with a waste heat source technology [71]. LCOH values may differ depending on the technology used to derive the hydrogen if directly connected to the wind plant. With a distributed methodology (one electrolysis system for each turbine), LCOH

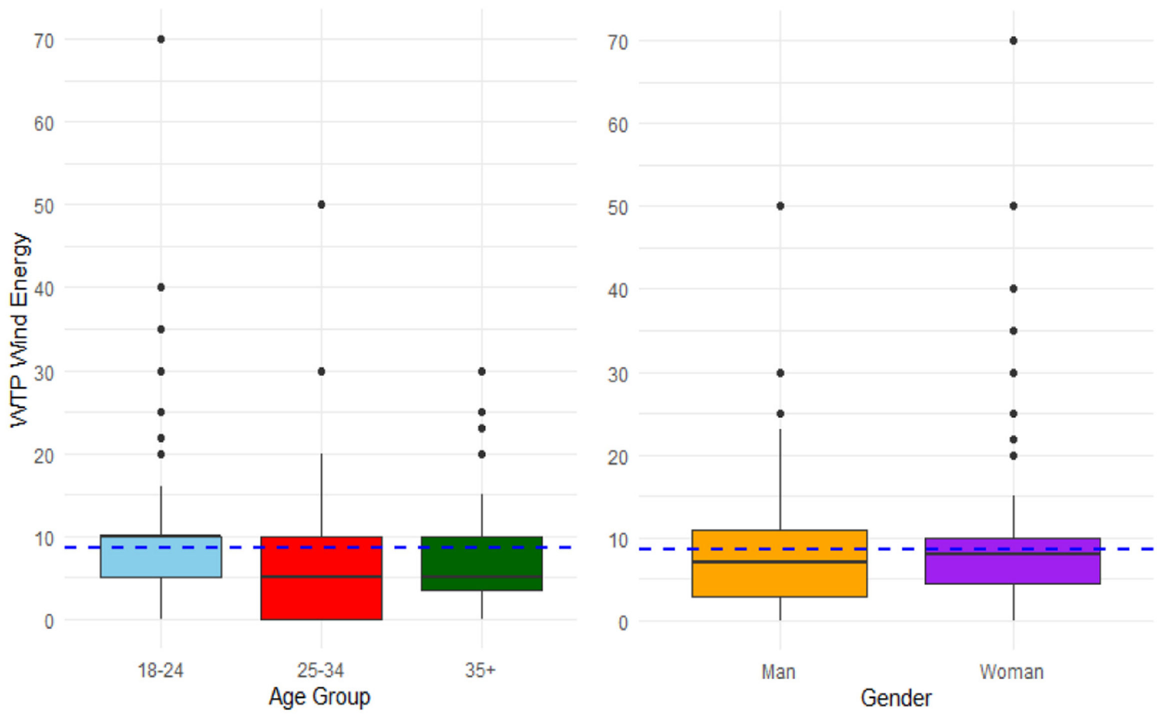

Fig. 11. Willingness to pay for hydrogen plants broken down by age group and gender.

results in 13.81 $/kg, with a centralized methodology (single offshore electrolysis system), LCOH results in 13.84 $/kg, and with an onshore technology (onshore electrolysis system), LCOH results in 14.58 $/kg [54]. These discrepancies significantly highlight the wide variations in LCOH values reported in the literature. This diversity can be attributed to multiple factors, including the size and capacity of the plants considered in the different studies, the cost of electricity, and the different investment costs of setting up electrolysis plants.

In the literature we find similar values to the results obtained in this study regarding people's level of knowledge about green hydrogen. In fact it is shown that 74 % of the population of Germany was not familiar with green hydrogen [45]. Other authors analyse the acceptance of hydrogen transport infrastructure via pipelines: 41.5 % of respondents belong to the group of supporters. The results of this work differ from what was obtained in the latter article. Before and after providing the definition of green hydrogen, the level of acceptance of building hydrogen plants in the neighbouring area was not as high but there was a high level of indecision [72]. Some analyses show different levels of concern about the safety of hydrogen use by the public [47]. Other authors report high knowledge of hydrogen, with 46 % of respondents reporting that they have heard of hydrogen energy and 43.5 % reporting that they are familiar with the topic [46]. In this work, we did not compare the acceptance level of green versus grey hydrogen, although WTP indicates a higher propensity. The literature shows that the level of public acceptance of green hydrogen was higher than that of blue and grey hydrogen [73]. Relative to wind power, similarities emerge with what has been proposed in other analyses, where people claim that the turbines of these plants are noisy and negatively impact the land and wildlife. In addition, the sample analysed believes that energy produced through wind is unreliable [74]. Issues also highlighted by other authors [75] as it was found that wind turbines have an impact on the environment and can affect nearby residents. Annoyance caused by wind turbine noise, intermittent shadow phenomenon, signal lights, and changes in the landscape has been identified as a factor influencing local acceptance. Higher WTP values of 28.5 % are recognized by citizens for the average monthly fuel cost when using green hydrogen. However, 43.5 % of respondents to the questionnaire administered, are not willing to pay more for green hydrogen fuel [76]. Regarding WTP, Italian citizens show a value of 13 % for renewable sources and 8 % for energy efficiency interventions. In addition, the female gender and older people tend to recognize a higher price in terms of green premium [51].

Sustainability options can take advantage of the benefits of storage [77], where various government policies can support green energy production [78]. Hydrogen can determine an important role toward carbon neutrality [79] and in this direction very important is the value recognized to emissions [7]. These changes highlight how renewable sources can support the transformation of operations management toward sustainability goals [80,81].

The economic and social analyses proposed in this work, combined with environmental data defined in the literature, propose green hydrogen as a vector moving toward sustainability. Against a European backdrop of energy fragility brought about by choices that have not enhanced internal resources, there is a new and growing concern arising from the multiple conflicts being generated around the world. Beyond the loss of human lives, this results in a perennial situation of potential geopolitical risks. In this way, the energy component becomes vital as much for business as for public administration and, consequently, for the lives of all citizens. Italy's potential is then decisive for Europe's energy future since it represents the gateway with African territory and in this direction the fundamental role that the Mattei Plan can play should be stressed.

Therefore, a national energy strategy is needed that is able to look at the overall situation, but this cannot be done at the expense of local communities. Consequently, the size of plants must be defined with a pragmatic, objective and inclusive approach. The construction of renewable energy plants is linked to the creation of infrastructure that allows the flow of these energy components, while also revitalizing timedated plants. The combination of all these decisions makes it possible to propose an operations strategy in the energy context that aims to provide green energy to as many stakeholders as possible by combining the development of industrial ecosystems (on-site production of industrial components), of consequent economic spillovers on the local territory but also nationally, as the competitiveness of companies supports their business expansion in international markets as well. The mix of skills and resources in the area should be integrated with the dissemination of knowledge among citizens, emphasizing their concerns and identifying solutions. In fact, decision-making gridlock results in inactivity that does not allow climate change to be remedied.

4. Conclusions

Green hydrogen can be defined as a sustainable operations strategy due to economic, environmental and social benefits within several activities that includes citizens and industries. This work confirms through socio-economic analysis how the combination of renewable energy sources with hydrogen technologies represents a viable strategy to have sustainable and flexible energy systems. In a European context moving toward decarbonization, there is a strong focus on renewables to gain energy independence and the use of natural gas, among fossil sources, to supplement energy needs. Within this framework, several states and companies are focusing on hydrogen, an energy carrier that can support not only SDGs 7 and 13, but can also reduce geopolitical risks through the Mattei Plan. However, it behoves us to produce green, not grey, hydrogen and to consider the amount of water needed for its production.

RO1 proposed a LCOH value of 3.60 €/kg that comes from a 30 MW wind and 18.5 MW electrolysis plant located in southern Italy capable of producing the first year of operation 1776,000 kg of hydrogen. In order to give robustness to the results obtained, alternative scenarios were analysed. Sensitivity analysis showed how relevant inflation is, since at constant and non-variable Opex, LCOH decreases to 3.03 €/kg. Similarly, it could increase to 3.90 €/kg indicating potential lower competitiveness. However, the factor that has the greatest impact is the Capacity factor, as going from 35 % to 25 % results in a LCOH of 5.25 €/kg. Scenario analyses pointed out that this economic indicator varies between 2.81–4.48 €/kg testifying to a strong variability that, moreover, was already underlined by the analysis of the reference literature on the subject. It was thus agreed to complete the economic picture with the risk analysis, which reports that 68.6 % of LCOH values vary between 3.20 and 4.00 €/kg when the Capacity factor is at 35 %. However, this value decreases to 1.7 % with a Capacity factor at 25 %. From here, two limitations of the work emerge: the first is an economic analysis that does not include revenues and therefore does not calculate plant profitability; the second concerns technical aspects since it is clear that proper plant location and appropriate plant sizing is also preparatory to economic results.

RO2 indicates the existence of a strong knowledge gap, as 72.5 % of Italians surveyed do not know the difference between green and grey hydrogen. In particular, it is men over the age of 35 who show the most knowledge on the topic. Adults confirm a greater knowledge on how it is made; however, improvements are also needed here as green hydrogen obtained from wind power gets a score of 4 out of 5, while the belief that green hydrogen can be obtained from fossil sources has a rating of "little agree" and not "not at all agree". Respondents know the uses of hydrogen, while they are not fully aware that water also plays an important role (3.5), and the same is also true for the potential risks associated with the plants (3.0). An attempt was then made to assess the NIMBY phenomenon and it emerges that citizens are not always open to the implementation of the plants even though they declare sustainable behaviours (the three questions on these aspects show values greater than 4). Similarly, however, the analysis of the questionnaire emphasized the strategic role of knowledge: having the description on the difference between green and grey hydrogen available, the willingness to install plants near home increases from 3.59 to 3.92 where the group of women aged 18–24 shows greater acceptance. WTP is about 10 % for green sources, and here it is the youngest who show the highest values. Shifting the focus from hydrogen to wind power, the WTP is 8.7 % for green energy while the propensity to accept wind power plants near home turns out to be 3.7.

The socioeconomic perspective highlights the third limitation of this work, which is that it does not consider the third environmental dimension of sustainability. However, such work applied to the Italian context can be easily replicated in other contexts. It emerges how economic variability can be contained with specific benchmarks and how hydrogen obtained from the wind+electrolysis mix supports the ecological transition and is economically attractive. However large-scale installations can trigger social outcry. Here the fourth limitation of the work emerges, which could consider a live experiment to see whether or not there is a fit with the results obtained from the online survey.

However, if we need to use our cell phones to connect with the rest of the world, if we need electricity for everyday uses, there also needs to be a greater maturity in the acceptance of plants near home because otherwise the development of renewables will not be able to take off in favour of the economic interests that characterize the world of fossil fuels. A sustainable approach, however, requires that the amount of energy produced is congruent with the area under consideration and is defined within a spatial energy planning framework. Greater knowledge of the subject is preparatory to the development of pragmatic models of sustainability, and major challenges can only be met with knowledge and not by maintaining the interests of a few and ideological approaches.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Francesco Bonesso: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Idiano D'Adamo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Massimo Gastaldi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Marco Giannini:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.susoc.2024.11.002.

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