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Carbon capture and storage is vital to reduce greenhouse gas emissions, albeit research on the public willingness to pay for it remains limited. Here we address this gap by considering information effects, development magnitude effects and prior familiarity relations on willingness to pay towards carbon capture and storage. Based on national-wide online survey targeting Danish public, conducted from June to August 2022, the contingent valuation method is employed. The study reveals that, irrespective of CO_2 reduction goals, enhancing familiarity with carbon capture storage can influence public support. Additionally, we estimate willingness to pay elasticities related to development magnitude using a scope test, ensuring economic significance and validity of our findings. Ultimately, this study provides valuable insights for policymakers and stakeholders, supporting and enabling the design of effective strategies to promote public support for carbon capture and storage, and contribute to global climate change mitigation efforts.

The escalating occurrence of abnormal weather phenomena and extreme natural events has underscored the pressing need for decisive action to address climate change. Global CO_2 emissions, primarily stemming from energy combustion and industrial processes, reached an unprecedented level in 2021, exacerbating the challenges of global warming[1]. Carbon capture and storage is identified as a vital technology capable of remarkably reducing greenhouse gas emissions and mitigating climate change[2–4]. By capturing CO_2 emissions from various sources and safely storing them underground, carbon capture and storage offers a pathway to substantial emission reductions. The widespread deployment of carbon capture and storage faces several challenges, including high costs, low public acceptance, and limited awareness[5,6]. Successful implementation of carbon capture and storage hinges on higher public awareness, familiarity and understanding in combination with public demand and willingness to support towards carbon capture and storage economically[5]. Effective strategies that can increase carbon capture and storage knowledge by providing accurate and trustful information thus play a pivotal role in shaping public opinion and increasing encouragement towards carbon capture and storage initiatives[7,8].

Despite its gravity, a mere 437 papers (10.2%) among 4,271 peer-reviewed papers on carbon capture and storage have addressed socio-political carbon capture and storage acceptance[9,10]. Of these, only five studies specifically apply state-of-the-art stated preference methodologies[11–13] to estimate willingness to pay for carbon capture and storage[14–17] as part of a broader set of low-carbon technologies attributes[14–16] or carbon capture and storage leakage mitigation[17]. Hence, published studies have not specifically explored the demand and willingness to pay for the carbon capture and storage technology. Furthermore, carbon capture and storage acceptance literature has predominantly focused on individual determinants, such as information effects or prior carbon capture and storage familiarity relationships, while overlooking the potential influence of the differences in carbon capture and Table 1 storage storage capacities, i.e. carbon capture and storage scope[18], on carbon capture and storage acceptance.

A paucity of studies on carbon capture and storage acceptance has examined the experimental effects of information and integrated relationship with prior knowledge or familiarity with carbon capture and storage[19–23]. For a review, see Zuch and Ladenburg[24]. Carbon capture and storage acceptance as a function of the scope and its interaction with information effects and familiarity have not been explored. Therefore, this emphasises the need for dedicated research, especially on estimating willingness to pay for carbon capture and storage, while considering carbon

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Table 1 | Information sets in the survey

Baseline
Carbon capture and storage (CCS) is a technology where CO_2 is captured at power plants or industries. The CO_2 is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO_2 stays there. In Denmark, we are already testing the possibilities of capturing CO_2 and storing it in two large old oil/gas fields in the North Sea.
Information 1: Baseline + Global CCU Usage
Carbon capture and storage (CCS) is a technology where CO_2 is captured at power plants or industries. The CO_2 is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO_2 stays there. The technology has been used abroad for almost 40 years, and in Denmark, the possibilities of capturing CO_2 and storing it in two large old oil/gas fields in the North Sea are being tested.
Information 2: Baseline + Global CCU Usage + Danish Natural Gas Storage Usage
Carbon capture and storage (CCS) is a technology where CO_2 is captured at power plants or industries. The CO_2 is transported via pipes/ships to the storage site and pumped deep into the subsoil, where nature itself ensures that the CO_2 stays there. The technology has been used abroad for almost 40 years and in Denmark the possibilities of capturing CO_2 and storing it in two large old oil/gas fields in the North Sea are being tested. Gas storage is not a new technology in Denmark. Since the mid-80 s and 90 s, millions of cubic metres of natural gas have been stored and extracted annually underground in Jutland (Lille Torup) and Zealand (Stenlille).

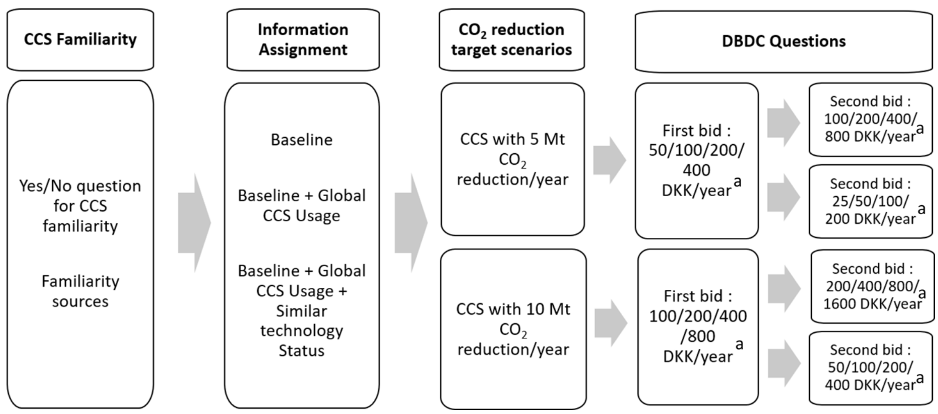


Fig. 1 | Willingness to pay for carbon capture and storage questionnaire process. a The costs presented were in Danish kroner in the real survey and converted into euro for data analyses.

capture and storage familiarity relationships, information and storage capacity scope tests to shed light on a critical research gap. This paper is a stated preference Contingent Valuation (CV) study investigating willingness to pay for carbon capture and storage and one of the few CV papers with the three dimensions' intertwined impacts. CV is an economic valuation method applied to estimate non-market goods based on asking a population sample about their willingness to pays to provide a given good or service[25].

In this study, we report from a Danish CV study of the willingness to pay for using carbon capture and storage technology to capture and store 5 million tons (Mt) CO_2/year or 10 Mt CO_2/year across two levels of carbon capture and storage familiarity and three information experiments. Denmark has taken notable strides to set up the country as a carbon capture and storage hub in Europe. Based on the pioneering carbon capture and storage initiative, Denmark enacted the climate agreement to make carbon capture and storage legal, expedite its approval process and utilise it in hard-to-abate sectors in June 2020[26]. The study is based on an online survey among a representative random sample of 3,390 residents across Denmark. The estimated willingness to pays exhibit significantly positive relationships with carbon capture and storage familiarity, carbon capture and storage scope capacity, age, education and household income of the respondents. The willingness to pay estimate for each household per ton of CO_2 mitigation ranges from 20 EUR/year to 37 EUR/year. By providing these comprehensive and holistic insights into the interconnections about willingness to pay towards carbon capture and storage, this study offers valuable guidance for policymakers and stakeholders in promoting carbon capture and storage adoption to understand and design effective policies and lower public opposition.

To investigate the integrated impacts on willingness to pay for carbon capture and storage, we conducted an online survey targeting a random sample of 55,000 Danish residents in the period July 27 to 31st of August 2022 (see Methods). The socio-economic sample characteristics closely resemble the national statistics (see supplementary Table 1). Our sample differs in terms of a lower share of respondents below 35, and a higher share of older respondents, electric/hybrid car and solar energy owners and respondents living in rural areas. The average household size, income and educational levels match the national levels.

The respondents were randomly assigned one of the two carbon capture and storage scope scenarios (CCS of 5 Mt CO_2/year (CCS_5M) and 10 Mt CO_2/year (CCS_10M)) and one of three information sets. A baseline information set provided a general overview of carbon capture and storage, while information set 1 included additional details on the global usage of carbon capture and storage technology. Information set 2 provided more specific information on Danish natural gas storage experiences on top of the content of information set 1. See Fig. 1 for an overview of the survey setup.

Following the presentation of information sets, they were asked to state their willingness to pays on behalf of their households to capture and store either 5 Mt or 10 Mt of CO_2/year in Denmark from 2030.

Results

The main willingness to pay estimates as a function of scope, familiarity, information and socio-demographics controls are presented in Table 2. The table includes two models for each carbon capture and storage scenario. Model I includes information effects and carbon capture and storage familiarity relationships, and Model II adds socio-economic controls to Model I. In order to address the potential issue of hypothetical bias, a common concern in willingness to pay studies, protesters and strategic bidders are excluded from our analyses[27–30], see Methods section.

Scope, information and familiarity impacts on willingness to pay

Respondents receiving the baseline information and having familiarity with carbon capture and storage, represented by the constant, have willingness to

Table 2 | Marginal Willingness to pay (EUR/household/year) estimates for Model I &II

	5 Mt of CO_2 /year reduction		10 Mt of CO_2 /year reduction		Scope test ΔWTP	
	Model I	Model II	Model I	Model II	Model I	Model II
Information 1	3.27	3.68	3.28	0.88	0.01	−2.79
	(2.95)	(2.92)	(4.89)	(4.79)	(5.78)	(5.67)
Information 2	8.10**	8.25**	−4.34	−6.69	−12.44*	−14.94**
	(3.05)	(3.02)	(4.89)	(4.79)	(5.71)	(5.61)
CCS familiarity	10.73***	9.45***	15.64***	9.51*	4.91	−0.65
	(2.55)	(2.63)	(4.10)	(4.13)	(4.95)	(4.99)
Female		1.24		0.13		−1.10
		(2.53)		(4.05)		(4.82)
Age		−0.10		0.31*		0.41**
		(0.08)		(0.13)		(0.16)
Education Level (Bachelor, Master & PhD)		9.86***		23.82***		13.95*
		(2.79)		(4.57)		(5.44)
Annual Household Income (divided by 1000)		0.07***		0.21***		0.14**
		(0.02)		(0.04)		(0.05)
Household size		−1.53		−0.36		1.17
		(1.17)		(2.01)		(2.36)
Electric/Hybrid car owner		4.84		1.97		−2.87
		(3.82)		(6.48)		(7.80)
Photovoltaics (PV) owner		−0.46		10.9		11.36
		(4.30)		(7.27)		(9.10)
Urban residence		−3.05		8.64		11.68*
		(3.00)		(4.57)		(5.41)
Income missing		−2.83		8.25		11.08
		(4.04)		(6.56)		(7.71)
Education – Do not know		−11.68		−59.85**		−48.17*
		(11.84)		(20.53)		(21.77)
Constant	47.11***	47.25***	77.92***	40.27***	30.81***	−6.98
	(2.29)	(6.05)	(3.83)	(9.76)	(4.49)	(11.70)
N	1660	1660	1730	1730		
LL(0)	−2082.0	−2082.0	−2460.6	−2460.6		
LL(β)	−2069.5	−2045.8	−2452.2	−2400.4		
McFadden R^2	0.006	0.017	0.003	0.024		
AIC	4149.0	4121.7	4914.4	4830.7		
BIC	4176.1	4202.9	4941.7	4912.5		

Standard errors in parentheses *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

pays for CSS_5M and CCS_10M of 47 EUR and 78 EUR in Model 1, respectively. The scope willingness to pay difference is significant. In Model II with socio-economic controls (see Table 3 for an overview of the coding of the variables), the constants represent the references group, including male respondents, being unfamiliar with carbon capture and storage, receiving the baseline carbon capture and storage information, living in rural areas, with no electric/hybrid car or PV panel on their houses, being 20 years old, having primary, high school, vocational training or vocational education, with an annual household income between 0-26,880 EUR and only one person in the household. The willingness to pays for the reference group are 47 EUR for CSS_5M and 40 EUR for CCS_10M, respectively. The difference in willingness to pay, which is 7 EUR, is not statistically significant based on the scope test in Table 2. Accordingly, the reference group's willingness to pay is not scope sensitive. As we touch upon later, the willingness to pay scope differences in Model I, are driven by age, education, income and urban/rural effects.

Familiarity with carbon capture and storage demonstrates a significant positive association with willingness to pay for the 5 Mt and 10 Mt CO_2/year reduction scenarios. The familiarity price premium in Model I is 11–16 EUR for carbon capture and storage and the differences is not significantly sensitive to the scenario scope. The marginal impacts of the information set 1 on willingness to pay in Model I and II, ranging from 1 to 4 EUR as shown in the first row of Table 2, are insignificant for both 5 Mt and 10 Mt. This demonstrates that information about international carbon capture and storage experience is not enough to drive a price premium for carbon capture and storage. Respondents are willing to pay 8 EUR more when shown information set 2, relative to the baseline information in the CSS_5M scenario. In other words, additional detailed information pertaining to Danish natural gas storage experience positively impacts the respondents' willingness to pay towards carbon capture and storage. However, the marginal WTPs for information 2, (-)4 EUR and (-)7 EUR are insignificant in the CSS_10M scenario. Accordingly, we can conclude that information

Table 3 | Data Variables and meanings

	Variables	Meaning		
Dependent Variables	5Mt_WTP	Willingness to pay for 5Mt scenario		
	10Mt_WTP	Willingness to pay for 10Mt scenario		
Independent Variables	Information 1	1: having CCS information set 1 0: not having CCS information set 1		
	Information 2	1: having CCS information set 2 0: not having CCS information set 2		
	CCS familiarity	1: having prior CCS familiarity 0: no prior CCS familiarity		
	Female	1: female, 0: male		
	Age	Individuals' age numbers – 20 (minimum age in the effective sample)		
	Education Level (Bachelor, Master & PhD)	Education level Lower (0): primary, high school, vocational training & education Higher (1): bachelor, master, and PhD		
	Annual Household Income (divided by 1000)	For each income brackets used in survey, the Danish Statistics (2022) average numbers are used.		
		Survey	Average	EUR convert
		<200,000 kr.	105,521 kr.	Survey14,182 EUR
		200,000-299,999 kr.	249,518 kr.	33,535 EUR
		300,000-399,999 kr.	349,494 kr.	46,972 EUR
		400,000-499,999 kr.	447,172 kr.	60,100 EUR
		500,000-599,999 kr.	547,310 kr.	73,559 EUR
		600,000-699,999 kr.	648,445 kr.	87,151 EUR
		700,000-799,999 kr.	749,467 kr.	100,728 EUR
		800,000-899,999 kr.	848,899 kr.	114,092 EUR
		900,000-999,999 kr.	948,172 kr.	127,434 EUR
		1,000,000-1,099,999 kr.	1,050,000 kr.	141,120 EUR
		1,100,000-1,199,999 kr.	1,150,000kr.	154,560 EUR
		>1,199,999 kr.	2,207,005 kr.	296,622 EUR
		Do not know / Do not want to answer	105,521 kr.	14,182 EUR
	Household size	The number of household members		
	Electric/Hybrid car owner	1: Having Electric or hybrid cars 0: No Electric or hybrid cars		
	Photovoltaics (PV) owner	1: having solar PV on properties 0: No solar PV on properties		
	Urban residence	1: living in urban areas 0: living in rural areas		
	Income missing	1: respondents who did not answer the Annual income 0: respondents who did answer the Annual income		
	Education – Do not know	1: respondents who did not answer the Education Level 0: respondents who did answer the Education Level		

set 2 does not significantly impact the respondents' willingness to pay towards carbon capture and storage for the 10 Mt scenario. The differences in the information 2 WTP effects across the two carbon capture and storage scenarios are significant and negative ((-)12 EUR and (-)15 EUR). The difference denotes that the information set 2 driving carbon capture and storage premiums or discounts are sensitive to the scope of scenarios. Building on the main results, we estimated willingness to pay for each household per ton of CO_2 mitigation, see Methods section. As delineated in Table 4, each household is willing to pay 20–37 EUR/ton/household/year to reduce CO_2 emissions using carbon capture and storage. These estimations are in the lower end compared to other studies[31–33].

Scope, Socio-demographic characteristics and willingness to pay

The results denote that the variables, gender, household size, and owning an electric/hybrid car or a private solar panel are not significantly related to the willingness to pay for carbon capture and storage. In contrast, socio-economic variables, age, education, income and living in urban areas show significant relationships with willingness to pay towards carbon capture and storage. The age estimate is insignificant in the CSS_5M scenario but significant in the CSS_10M scenario, with an estimated WTP of 0.3 EUR per year of age. Older respondents have a higher willingness to pay for using carbon capture and storage to mitigate 10 Mt of CO_2/year. The age estimates significantly differ between the two scenarios, denoting an age-induced scope effect of willingness to pay for carbon capture and storage. Respondents in urban areas have a 12 EUR higher willingness to pay for CSS_10M scenario than those living in rural areas. The urban willingness to pay relationship is significantly scope sensitive. Higher education attainment is associated with significantly higher willingness to pay levels. Respondents with at least a bachelor's degree have a 10 and 24 EUR higher willingness to pay for the CSS_5M and CSS_10 scenarios, respectively. The education willingness to pay estimates are significantly scope sensitive. Finally, we find significant income effects. For each around 13,440 EUR interval in an annual household income, the willingness to pay increases by 70 EUR and

Table 4 | Willingness to pay (EUR) per ton of CO_2 mitigation/household depending on each scenario

	5 Mt Scenario		10 Mt Scenario	
	Model I	Model II	Model I	Model II
No CCS familiarity + Baseline Information	26.27	31.23	21.73	19.99
Information 1	-[a]	-[a]	-[a]	-[a]
Information 2	30.79	35.83	-[a]	-[a]
Yes CCS familiarity	32.26	36.50	26.09	22.64

Notes: The total number of households in Denmark is 2,788,291 as of 2022. a) Not statistically different as compared to the baseline information set.

210 EUR for the CSS_5M and CSS_10M scenarios, individually. We used household income brackets from Statistics Denmark[34] and the mean values of each bracket to define these income intervals. The significant income scope effects are in Fig. 2, including income willingness to pay elasticities. The income effects drive a scope wedge between the willingness to pay for CSS_5M and CSS_10M. Likewise, the estimated income elasticity estimates increase from 0.063 – 0.328 in the CSS_5M and 0.113 – 0.481 in the CSS_10M scenarios. These are in line with income elasticities for other willingness to pay CO_2 mitigation studies[23]. The income missing variable for the respondents who did not report their income levels was coded as having an income equal to the lowest income group (14,182 EUR). The estimates are (-)2.83 EUR and 8.25 EUR, denoting that the respondents who did not report their income levels have insignificantly indifferent willingness to pays compared to the respondents with the lowest income level. The variable Education – Do not know is a dummy variable coding for the respondents who did not report their education level. The associated marginal willingness to pay estimates are (-)12 EUR and (-)60 EUR, the latter being significant. The results denote that these respondents have a lower willingness to pay than those with a primary, high school or vocational education. The differences in willingness to pay between the respondents who did not report their educational levels and the respondents with at least a bachelor's degree are 22 EUR and 84 EUR. Only the latter is significantly different from zero.

Scope elasticities

The scope elasticity is central for establishing how willingness to pay for carbon capture and storage varies regarding the level of CO_2 captured and stored. A scope elasticity larger than zero and lower than one denotes decreasing marginal willingness to pay for additional units of CO_2 captured and stored, whereas an elasticity above 1 suggests increasing marginal willingness to pay for additional units of CO_2 captured and stored. Table 5 reports the sample average scope elasticities for the different information experiments and across socio-demographic variables.

The sample average scope elasticities reflect the willingness to pay differences in Table 5 between the two carbon capture and storage scenarios. Focusing on age, the scope elasticity increases from 0.588 in the youngest age group to 1.056 in the oldest age group (75 + years). Accordingly, the oldest respondents appear to have increasing marginal willingness to pay for additional units of CO_2 being captured and stored. The scope elasticity also increases with income, showing an increasing marginal willingness to pay for the two highest income sub-groups.

Discussion

Understanding factors influencing public willingness to pay for carbon capture and storage is essential for successfully implementing carbon reduction strategies. This paper's main findings denote that carbon capture and storage familiarity, carbon capture and storage scope capacity, age, education and household income of the respondents play a important role in shaping the willingness to pay for carbon capture and storage. An equally important finding is that experimental information focusing on international and national gas storage experience has little causal effect on willingness to pay.

Although no technologies are completely unfeasible due to social opposition, low public acceptance severely impedes their implementation. Ladenburg et al.[35] find that onshore rural and urban carbon capture and storage and nearshore carbon capture and storage are the least accepted technologies to address climate change among the Danish public based on the answer from a national survey. Offshore carbon capture and storage ranks in the middle in terms of public acceptance across thirteen CO_2 mitigation strategies. These strategies include wind power, solar panels and carbon capture and storage in various locations, district heating, energy saving technologies, and nuclear power. However, although carbon capture and storage still has relatively lower awareness and acceptance levels among the public, we showcase positive willingness to pays towards offshore carbon capture and storage. In this perspective, our scope-independent positive willingness to pay for carbon capture and storage across familiarity relationships and partly information effects illustrates a potential pavement for future carbon capture and storage support. Jointly, the results highlight the

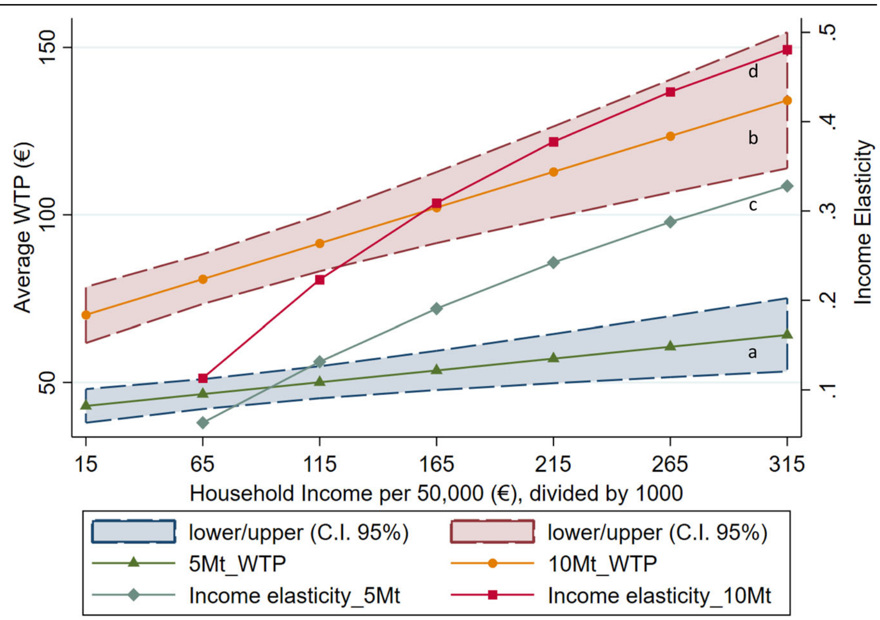


Fig. 2 | Income effects (€ per household/year). **a** Willingness to pay for 5 million-ton carbon capture and storage capacity scenario (green triangle line) is presented depending on household income levels with 95 confidence level (blue dash-line square). **b** Willingness to pay for 10 million-ton carbon capture and storage capacity scenario (orange circle line) is presented depending on household income levels with 95 confidence level (red dash-line square). **c** Income elasticity for 5 million-ton carbon capture and storage capacity scenario (light blue diamond line) is presented contingent on household income levels. **d** Income elasticity for 10 million-ton carbon capture and storage capacity scenario (red square line) is presented contingent on household income levels.

Table 5 | Sample average scope elasticity estimates

		Model I	Model II
No CCS familiarity + Baseline Information[a]		0.739	0.824
Information 1[a]		0.703	0.735
Information 2[a]		0.428	0.476
Yes CCS familiarity[a]		0.708	0.721
Annual Household Income (divided by 1000, EUR)	0-30		0.719
	31-90[b]		0.807
	91-140		0.878
	141-190		0.935
	191-240		0.983
	241-290		1.024
	291-		1.059
Education Level			0.885
Age	20-35		0.588
	36-45		0.702
	46-55		0.786
	56-65[c]		0.867
	66-75		0.946
	75-		1.056
Urban residence			0.878
Female			0.808
Household size			0.774
Electric/Hybrid car owner			0.733
Photovoltaics (PV) owner			0.990

[a]The estimations for scope elasticity are based on the average of the other socio-demographic variables.
[b] The mean of annual household Income (divided by 1000, EUR) are 79.17 EUR for 5M-ton and 73.59 EUR for 10 M-ton, respectively.
[c]The mean age is 56 for both 5 M- and 10 M ton cases.

importance and the challenges policymakers face in designing strategies for promoting public support concerning carbon capture and storage deployment. First of all, the results showcase that direct information strategy, illustrated by our information experiments, might positively impact the willingness to pay and support for smaller scale carbon capture and storage projects but not larger scale projects. Furthermore, compared to the information effects, the relatively larger and scope-consistent relationship between carbon capture and storage familiarity and willingness to pay suggests that actions could be more efficient if directed towards increasing familiarity about carbon capture and storage through education to the public in general[36–38], rather than single information outbursts.

Our scope willingness to pay results demonstrate that individuals exhibit a significantly greater willingness to pay when presented with more ambitious carbon capture and storage targets, having higher income and education levels, being older, and residing in urban areas. However, respondents who are younger, have lower incomes and shorter educations and reside in rural areas are not sensitive to the scope. The low income and scope insensitivity could relate to a lack of ability to pay. The lower acceptance of offshore carbon capture and storage among younger Danes and those living in rural areas found in Ladenburg et al.[35] can explain the scope insensitivity among the younger and rural respondents. However, the willingness to pay scope insensitivity among respondents with shorter educations cannot be linked to lower offshore carbon capture and storage support. Following the discussion in Dugstad et al.[18], the socio-economic differences in the willingness to pay scope call for further research.

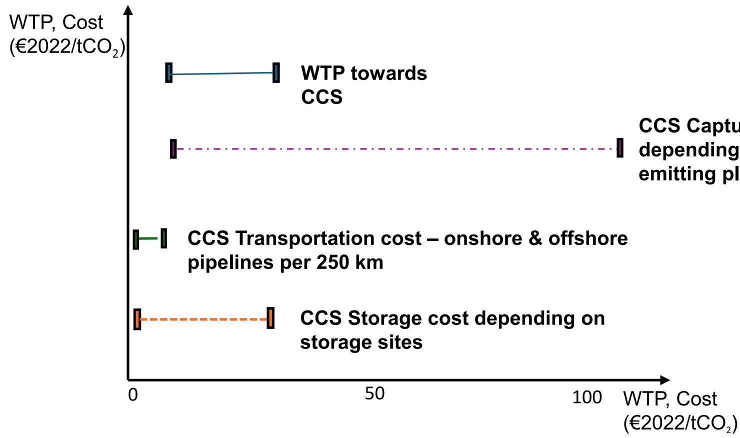
Our results also show that each household's willingness to pay for mitigating CO_2 through carbon capture and storage technology ranges from 20–37 EUR/ton/year. This finding underscores a critical financial gap between the willingness to pay for carbon capture and storage and costs, particularly for the capturing process, as illustrated in Fig. 3. While transportation and storage costs fall within the range of willingness to pays for carbon capture and storage, a substantial financial shortfall remains for covering the entire process, including capturing, transporting and storing CO_2. Therefore, there is a need to simultaneously drive down carbon capture and storage costs and drive up public willingness to pays for carbon capture and storage to bridge this gap. The substantial income and educational willingness to pay effects suggest that these groups are particularly willing to pay for the use of the technology and, therefore could be targeted to drive up willingness to pays towards carbon capture and storage. Targeting people with higher levels of education could be challenging. However, a carbon capture and storage tax, as used in the survey, might be a good tool to increase and co-finance the penetration of carbon capture and storage. From an equality perspective, the use of a fixed carbon capture and storage tax on the household level, as done on the survey, will have adverse distributional effects. Households with higher income will have consumer surpluses in the case of a fixed tax, while lower income households will have negative consumer surpluses. However, imposing an income-dependent carbon capture and storage tax can achieve a more even distribution of costs and benefits across households with different income levels. An income-dependent carbon capture and storage tax would also consider higher-income households having a higher CO_2 footprint (CF) than lower-income households through a higher expenditure CF elasticity[39].

Methods

Data collection

The data on Willingness to Pay (WTP) for Carbon Capture and Storage (CCS) was obtained through an online national energy perception survey conducted among Danish households. The survey was designed to investigate public attitudes towards diverse energy technologies and gather insights into the WTP for CCS. A total of 55,000 individuals were randomly

Fig. 3 | Willingness to pay (WTP) for carbon capture and storage (CCS) estimates and costs comparison (€2022/tCO$_2$). **a** Emitting plants are Coal-fired power, Gas-fired power, Iron & Steel, Refineries & naturel gas processing, Cement production, Natural gas combined cycle, Oxyfuel combustion. **b** Storage site are depleted oil and gas field onshore & offshore, Saline formations onshore & offshore. **c** Based on Budinis et al.[89] study, the CCS cost estimates are modified and converted into 2022-euro values.



CCS WTP vs. CCS Cost (€2022/tCO$_2$)	Min	Max
WTP towards CCS	19.9	36.5
CCS Capturing cost depending on emitting plants [a, c]	21.5	118.3
CCS Transportation cost – onshore & offshore pipelines per 250 km [c]	1.4	16.2
CCS Storage cost depending on storage sites [b, c]	1.7	33.8

selected from the population using personal identification numbers, following approval from the Danish Health Data Authority. One-third (18,333 individuals) were randomly assigned to the Willingness to Pay for Carbon Capture and Storage survey. The other respondents were randomly assigned to a survey concerning attitudes towards energy technologies and a preferences for heat sources survey. On June 27, 2022, the selected respondents were invited to participate in the survey through their digital mailboxes, E-boks. A reminder was sent to respondents who had not answered on August 18, 2022. The survey finalised on August 31st, 2022, after 3 days of no further questionnaire completions. Of the 18,333 invited respondents, 4,193 answered, resulting in a response rate of 22.3%.

The demographics of the respondents for the effective sample are represented in the Supplemantary Table 1. The sample differs in terms of a lower share of respondents below 35, and a higher share of older respondents[40,41], electric/hybrid car and PV owners and respondents living in rural areas. The higher share of older respondents with electric/hybrid cars and PV owners could represent higher survey participation among people with a (behavioural) interest in energy topics. The higher shares of rural and older respondents are more challenging to explain. International studies reveal varying levels of survey participation across age groups. Our age survey participation selection relationships are in line with Danish national representative surveys[42]. The average household size, income and educational levels match the national levels.

Experimental design

The WTP for Carbon Capture and Storage survey was designed to first enquire about the respondents' familiarity with CCS technology and familiarity sources. Then, the respondents were randomly assigned to three information sets, irrespective of their CCS familiarity. Following the information sets, two CCS development magnitude (scope) scenarios, 5 Mt and 10 Mt, were presented to each 50% of respondents. Depending on the scope scenario received, respondents were given different price levels corresponding to their assigned scenario. For instance, in the 5 Mt scenario, respondents were on average shown lower price levels for the first bid compared to the 10 Mt scenario. Depending on their responses to the initial bid, second bid prices were provided at half or double the first bid.

Scenario development

The survey instrument was developed iteratively through a comprehensive process that involved a literature review, interviews with regulation and energy experts, individual survey tests, and pilot testing with 229 respondents. Besides testing the overall survey, the individual and pilot tests were also used to determine the appropriate CCS tax levels used in the WTP questions. The pilot test revealed that the maximum tax levels were rejected in 75% of the cases, while the minimum tax levels were rejected in 10% of the cases. During the CCS scenario development, we consulted reports from the Danish Energy Authority (DEA)[43] and CCS experts concerning the potential risk of CO_2 leakages. The Danish reports conclude that CCS is a mature technology with small risks of leakages and that no CO_2 leakages have been monitored from existing geological storage sites. Furthermore, during the consultations, the DEA clarified that CCS will not be implemented if any uncertainties are related to potential low leakage risks. In addition, the literature is quite ambiguous regarding the effect/relationship between risk information and CCS acceptance/preferences. Some studies find a negative relationship between risk information and CCS acceptance[19,44–48], whilst others find a positive relationship[22,23,49–55]. Therefore, we do not address the issue of potential small negligible CCS leakages in the CCS scenario. The relationship between CCS WTP, risk perceptions, and risk information calls for further research.

The two scenarios, 5 Mt and 10 Mt of CO_2/year were chosen based on inspiration from the report by the Danish Energy Authority in 2021 on the Danish potential for CCS[43]. The report estimates the CCS potential to be 4.5–9 Mt CO_2/year, but also stresses out the notable uncertainties related to the potential capture and storage estimates. Accordingly, we decided to use 5 Mt (low estimate) and 10 Mt (high estimate) in the scenario description. The text in the information experiments were developed through an iterative process with CCS expert interviews, individual survey tests and the pilot test. The main text body (baseline information) was developed to briefly introduce the CCS technology, where the CO_2 is captured, how it is transported and where it is finally stored. In the text, we specifically mention both power plants and industries as point CO_2 sources, as the publicly available CCS literature from DEA and other sources differentiate between CO_2 emissions from power plants and the industry. The CCS scenario does not focus on whether or not CCS is carried out as a public or private investment project but solely on the use of the technology. A prior expectation is that the provision of CCS facilities, either public or private, should not impact individual CCS valuation, everything else being equal[56]. Naturally, we would expect differences in WTP based on the access conditions to the goods being provided, such as publicly provided goods for all vs. privately provided goods only for specified groups[57]. These expectations do not apply to a public good like CO_2 capture and storage. However, if respondents associate different trust levels with public vs. private investments in CCS, the economic valuation might be sensitive to the public vs. private investment framings[58,59]. This calls for further research.

Addressing limitations of hypothetical choices

Ideally revealed data on actual economic transactions by consumers is analysed to estimate the demand and willingness to pay for energy services, such as the purchase of gas and electricity[60]. However, in the case of CCS, revealed data does not exist. As an alternative, economists turn towards stated preferences methods like Contingent Valuation[61,62] and Choice Experiments[63,64]. Given the hypothetical nature of stated preferences, the elicited demand and preference relations can be subjected to several biases. Hence, the survey includes features designed to minimise them. First, stated preferences can suffer from hypothetical bias[65–67], where people overstate the WTP relative to their real WTPs. In order to reduce the bias, respondents for our survey were given a consequentiality script[68–70], which informed them that their answers could influence the decision-making regarding CCS implementation. The respondents were also encouraged to carefully consider their household's budgets and the hypothetical nature of stated preferences while determining their WTPs via a short Cheap Talk[71,72]. Finally, to remedy ex-post potential hypothetical bias among respondents, the respondents were asked to mention how confident they were in their stated WTP levels on five point scale ranges: Very confident, Confident, Neither/nor, Not confident and Very unconfident[73–77]. Excluding the 112 respondents, who are not confident in their answers, does not change the estimated WTPs significantly for the CSS_5M and CCS_10M scenarios. The models and WTP comparisons are in the Supplementary Table 2.

Often, a binary dichotomous choice is preferred due to the incentive-compatible characteristics[78]. We estimated models using only first bid presented to the respondents, yielding similar preference relations, albeit significantly higher levels of WTP and standard errors (see supplementary Table 3). Utilising the second bid in the WTP estimation thus results in both lower WTP and standard errors.

Hypothetical choices can also be insensitive to the number/amount of the resource under investigation so that the WTP for goods does not increase with the amount of goods provided[79–81]. To conform to economics theory, the WTP for goods has to correlate with the amount of goods being provided. To ensure the validity of our survey, we test how WTPs vary across the CCS scenarios, using an external scope design, in which respondents stated their preferences for 5 Mt or 10 Mt of CCS storage facilities. As the results denote, the study passes the scope test, as shown in Table 5 regarding the scope elasticity

Negative or positive responses to hypothetical WTP questions can be subjected to protest or strategic biases[27–30]. Protest bias emerges when the motive for rejecting (twice in double-bounded dichotomous choice, DBDC) a bid is driven by non-economic reasons, such as disliking the payment vehicle or believing that others should pay. Likewise, strategic bias is presented when the motive for accepting a bid (twice in DBDC) is not related to the trade-off between the price and the good in focus. Our study identified protest and strategic bids using follow-up questions after the respondents stated their preferences. Respondents who stated the following three reasons for not wanting to pay for CCS (answering No/No), were classified as protesters: "CCS is an advantage for society and the environment, but I do not want to pay for the technology", "The state should pay for CCS", and "I already pay enough in tax". Respondents who stated the following two reasons and wanted to pay (answering Yes/Yes), were classified as strategic bidders: "I support the use of CCS regardless of the cost" and "It's not real money, so I have not emphasised the size of the amounts". The Protest (8.35%) and Strategic (10.76%) respondents were removed from the sample. Finally, a positive relationship between income and WTP is widely perceived as a critical indicator of internal validity. We find substantial and significant income effects in both our valuation scenarios[82,83].

Analysis

The DBDC contingent valuation method was employed to elicit respondents' WTP. Each respondent was presented with a sequence of two bids and asked to respond with a Yes or No vote indicating whether their WTPs equalled or exceeded each bid[43]. The first bids for the 5 Mt scenario ranged from 7 to 54 EUR/household, while the first bids for the 10 Mt scenario ranged from 13 to 108 EUR/household.

The second bid in each scenario was contingent on the response to the first bid[84]. If the response to the first bid was No, a lower second bid was provided, whereas a higher second bid was presented for a Yes response. The second-round bid levels ranged from 3 to 108 EUR/household for the 5 Mt scenario and from 7 to 215 EUR/household. Respondents were randomly given two scenarios and bid levels to minimise the possibility of starting point bias[85].

The DBDC data is analysed within the Random Utility Model (RUM) framework[86]. The WTP can be modelled as follows[25]:

$$WTP_i(z_i,\ u_i) = z_i\beta + u_i$$

where WTP_i is the WTP of individual i, z_i is a vector of explanatory variables, β is a vector of parameters to be estimated and u_i the error term and assume that $u_i \sim N(0, \sigma^2)$.

Based on utility maximisation, an individual is expected to answer 'yes' to the base bid, A, when their WTPs are greater than the suggested bid amount, i.e., when $WTP_i > t_i$[85]. Then, in the DBDC questions, there are four possible responses if letting t_1 be the base bid and t_2 be the following bid[25]. Their four corresponding possibilities are also as follows:

$$\text{Yes|Yes} \Rightarrow \text{WTP} \geq t_2 \ \Pr(\text{Yes|Yes}) = \Phi\left(z_i{\prime}\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right)$$

$$\text{Yes|No} \Rightarrow t_1 \leq \text{WTP} < t_2 \ \Pr(\text{Yes|No}) = \Phi\left(z_i{\prime}\frac{\beta}{\sigma} - \frac{t_1}{\sigma}\right) - \Phi\left(z_i{\prime}\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right)$$

$$\text{No|Yes} \Rightarrow t_1 > \text{WTP} \geq t_2 \ \Pr(\text{No|Yes}) = \Phi\left(z_i{\prime}\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right) - \Phi\left(z_i{\prime}\ \frac{\beta}{\sigma} - \frac{t_1}{\sigma}\right)$$

$$\text{No|No} \Rightarrow \text{WTP} < t_2 \ \Pr(\text{No|No}) = 1 - \Phi\left(z_i{\prime}\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right)$$

One way to obtain β and σ is to estimate a likelihood function to obtain them directly. The function that needs to be maximised in order to find the parameters of the model is[25]:

$$\sum_{i=1}^{N}\Bigg[I_{yn}ln\left(\Phi\left(z_i'\frac{\beta}{\sigma} - \frac{t_1}{\sigma}\right) - \Phi\left(z_i'\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right)\right) + I_{yy}ln\left(\Phi\left(z_i'\ \frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right)\right)$$
$$+ I_{ny}ln\left(\Phi\left(z_i'\frac{\beta}{\sigma} - \frac{t_2}{\sigma}\right) - \Phi\left(z_i'\frac{\beta}{\sigma} - \frac{t_1}{\sigma}\right)\right) + I_{nn}ln\left(1 - \Phi\left(z_i'\beta/\sigma - t2/\sigma\right)\right)\Bigg]$$

where $I_{yn} = 1$ if the ith response is (yes, no) and 0 otherwise, $I_{yy} = 1$ if the ith response is (yes, yes) and 0 otherwise, $I_{ny} = 1$ if the ith response is (no, yes) and 0 otherwise, and $I_{nn} = 1$ if the ith response is (no, no) and 0 otherwise[85]. Using this maximum likelihood estimation, the β and σ can be obtained directly[25].

Income effect

Since the income is a strong determinant of the respondents' WTP, we estimated average WTPs for two scenarios depending on different income ranges. Building on the DBDC results, we measured average WTPs across diverse income brackets, while taking into account the mean values of other socio-demographic variables excluding the coefficients associated with information and CCS familiarity to focus on the income effects. When it comes to the income elasticity, we computed an arc income elasticity[87], $\varepsilon_{Income} = \frac{\Delta WTP}{\Delta Income} \frac{(Income_1 + Income_2)/2}{(WTP_1 + WTP_2)/2}$ as to various income ranges to figure out the extent to which the average WTP varies in response to changes in income.

Scope elasticity

We estimated the scope elasticity of WTP as a measure of economic significance concerning our WTP results. Elasticity is to assess the plausibility of the change in one economic variable along with the change in another[79]. In that sense, the scope elasticity can be measured $\varepsilon_Q = \frac{dWTP}{dQ} \frac{Q}{WTP}$, where Q is a quantitative measure of scope change. However, since many CVM studies only include base and scope scenarios, meaning that it is not enough to split sample treatments to estimate a continuous WTP function. Hence, the point elasticity, the arc elasticity: $\varepsilon_Q = \frac{dWTP}{dQ} \frac{\bar{Q}}{\overline{WTP}}$, where the horizontal bar represents the midpoint of a line segment was employed in our study[88]. In our scope elasticity estimation in Table 5, we considered the mean of other socio-demographic variables for the baseline, information 1 & 2 and CCS familiarity cases. For example, the WTP estimation for information 1 builds upon the coefficients of constant, information 1 and the socio-demographic variables multiplied by their respective national mean values. Concerning income and age, the WTP estimation considers the coefficients of corresponding variables multiplied by each sub-group level, on top of the constant and other socio-demographic coefficients multiplied by each mean. As to the remaining socio-demographic variables, the WTP segments are derived from the constant and other socio-demographic coefficients multiplied by their respective national mean values and the corresponding variable value.

WTP per ton for each household of CO_2 reduction

The WTPs per ton for each household to mitigate CO_2 emissions are calculated based on the main WTP results, given the information, and the impacts of CCS familiarity. We considered the constant and statistically significant information, familiarity and socio-demographic variables in each CO_2 reduction scenario: annual household income (divided by 1000) and education for CCS_5M and annual household income (divided by 1000), education, and age for CCS_10M. To estimate the WTPs per ton of CO_2, the significant socio-demographic variables are multiplied by the corresponding national population means. For instance, the income average of the national population, 79,390 EUR is multiplied (79.39, as the income variable is divided by 1000 EUR) by the coefficient of income. Following this, we multiply the estimated WTPs by the number of households as of 2022, 2,788,291. The estimated WTPs are divided by 5,000,000 (CCS_5M) and 10,000,000 (CCS_10M) tons to obtain a WTP/ton of CO_2 mitigation.

Inclusion and ethic statement

The research project and the sample collection were granted ethical approval the Danish Health Data Authority. In the beginning of the survey invitation letter, full and informed consent was provided to all participants. The consent also notified the handling of participant data in a complete anonymous manner in accordance with the General Data Protection Regulation and that any data would be analysed in an aggregate fashion, which disables personally identification. The we also informed the participants about they right to withdraw their participation at any time and conditional on participation, the length of time the data would be stored before deletion. The research specifically aims at obtaining a better understanding public preferences for carbon capture and storage using a survey under different information and technology capacity scenarios. No local researchers have been included so far. Prior to the research, the different author team roles and responsibilities were discussed and elaborated upon. We made deliberate attempts to have taken into account local and regional research in the citations

Data availability

The data set generated for this study is available at https://doi.org/10.5281/zenodo.12748785.

Code availability

The analytic code generated for this study is available upon request from the authors.

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Author contributions

Jiwon Kim was involved in the conception and development of the study, data analyses, analyses of the results, visualisation, writing of the paper, revising of the paper, and editing. Jacob Ladenburg was involved in the conception and development of the study, data analyses, analyses of the results, writing of the paper, revising of the paper, and editing.

Competing interests

The authors declare no competing interests.

Additional information

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