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Exploring heterogeneity in marine energy preferences: insights from Chile

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Marine energies can reduce carbon emissions, diversify energy supply, and improve energy security worldwide. However, no form of energy generation is without a social and environmental impact, and these impacts can lead to tension and conflict between governments, energy providers, and communities. Understanding heterogeneity in public preferences towards marine energy is critical to formulating appropriate policies and targeted development strategies. This study used a choice experiment with the Chilean public to elicit preferences and evaluate critical attributes of marine energy projects. Through a best-worst scaling (BWS) methodology, respondents indicated which aspect of marine energy installations they considered most and least important. Data were analyzed using a scale adjusted latent class model. Using data from 1,200 respondents, five preference classes and two scale classes were identified. The two largest preference groups have markedly different preferences. The first preference class is mainly concerned about impacts on marine fauna. Individuals in this group are more likely to be younger, have higher incomes and higher education levels compared to the sample average. The second preference class is most concerned about the cost of energy supply. Individuals in this group are older, less wealthy, and have lower education levels compared to the sample average. Results also show high levels of public distrust in both energy companies and government energy institutions, highlighting the need to shift from “consultation” to binding in early-stage public participation in marine energy development. Our approach and results are relevant to other areas transitioning to renewable energy matrices that need to design sustainable and acceptable marine energy systems.

KEYWORDS

best-worst scaling, human dimensions, hydrokinetic energy, ocean energy, tidal energy, wave energy, perception

1 Introduction

Marine energies have the potential to reduce carbon emissions, diversify energy matrices, and improve energy security worldwide (Boehlert and Gill, 2010; Uihlein and Magagna, 2016; Chowdhury et al., 2021; Weiss et al., 2018). There are multiple marine energy sources and technologies (Bedard et al., 2010). However, none are free from social and environmental impacts (Bonar et al., 2015; Copping and Hemery, 2020). These impacts can lead to tension and conflict between governments, energy providers, and communities (Copping et al., 2020), with negative implications for human wellbeing and the effective and sustainable development of marine energies.

Studying public perceptions and preferences toward new technologies, such as marine energy, helps to understand and explain what the public knows and thinks and how they might respond to its deployment (Boudet, 2019; Gelcich and O'Keeffe, 2016). Wiersma and Devine-Wright (2014) explored the reasoning behind oppositional and supportive public responses to marine energy developments in Europe and USA. They found that concerns associated with oppositional responses included: ecological impacts, visual impacts, and procedural unfairness, among others. On the other hand, views associated with supportive public responses included economic benefits, attracting tourists, and improving energy security. Previous research also suggests that public acceptance of renewable energy projects depends not only on perceptions of environmental and economic impacts but also on whether decision-making processes are perceived as fair and inclusive and whether project benefits and costs are distributed equitably among affected communities (Ponce et al., 2024; Estévez et al., 2021).

Ruano-Chamorro et al. (2018) reviewed the literature on human dimensions of marine energies to explore gaps and challenges and found: "a lack of understanding of the influence of socio-demographic factors on attitudes towards this type of energy". They also found a pressing geographic bias, 86% of articles were from developed countries, specifically the UK (45%) and the United States (28%). In addition, only one study was from the southern hemisphere (New Zealand), and none were from Latin America. Unfortunately, an understanding of factors that might support or impede the development of marine energies from the perception of civil society has still not received the attention it deserves.

Many coastal nations are in a unique position to develop sustainable and acceptable marine energy. This is particularly true for Latin-American countries, such as Chile, with over 4,000 km of coast exposed to consistent and high Pacific swells that boost wave energy. In addition, studies have identified Chile as a region with high wave energy potential in global energy resource estimations (Cornett, 2008; Gunn and Stock-Williams, 2012) For example, Lucero et al. (2017) assessed wave energy resources along the central coast of Chile (Latitude: 32.5° S to 42.5° S) and estimated an increase in power with increasing latitude, fluctuating between 20 and 35 kW/m in nearshore areas.

In 2014, the Chilean Energy Ministry developed national action plans to achieve reliable, sustainable, and inclusive energy (Simsek et al., 2019), committing to reach 70% generation from renewable sources by 2050 (Comité Consultivo de Energía 2050, 2015; Ministerio de Energía, 2014; Nasirov et al., 2019). Additionally, Chile's electricity demand is projected to increase steadily over the next two decades, rising from 71.6 GWH in 2019 to 108.9 GWh in 2039 (Mattar et al., 2021). These estimations that are likely to increase with the energy needs associated with Artificial Intelligence data center requirements in Chile.

While Chile's renewable energy transition has been driven primarily by the rapid expansion of solar photovoltaic and onshore wind technologies, marine renewable energy remains at an early stage of development despite the country's exceptional wave and tidal resource potential (Simsek et al., 2019; Flores-Fernández, 2020; Mattar et al., 2021; Ponce et al., 2024). Although wave energy has progressed through pilot initiatives such as the MERIC PB3 wave energy converter, first deployed in central Chile in 2021 (Ponce et al., 2024), public familiarity with marine energy technologies remains moderate. A recent national survey found that only about half of respondents (53%) had previously heard of wave or tidal energy (Ponce et al., 2024), suggesting that civil society engage with these technologies with limited prior knowledge.

Given that the development and deployment of marine energy are still in their infancy in Chile, there is a timely opportunity to assess public preferences towards marine energy as a way to anticipate possible social responses before implementing marine energy projects. A common practice has been to make general assumptions about how civil society responds homogeneously to new energy developments without considering that communities are highly heterogeneous in their socio-economic characteristics, attitudes, and values (Wolsink, 2018). From a policy perspective, identifying heterogeneity in preferences is essential to designing interventions that can target groups with different preference structures.

This study uses Chile as a learning platform to identify attributes of marine energy projects that the public (civil society) considers most important, assess heterogeneity in public preferences, and determine what factors may explain this heterogeneity. Results will ideally aid in predicting possible social responses to marine energy projects and inform the design of policies in ways that accommodate the public's needs and priorities from the beginning (Gelcich and O'Keeffe, 2016).

This paper focuses on Chile's most promising marine energy technologies: tidal and wave energy through the use of best-worst scaling and scale adjusted latent class modelling. Our approach and results are relevant to other areas transitioning to renewable energy matrices and which need to facilitate communication between policymakers, technologists, stakeholders, and the public to inform the design of sustainable and acceptable marine energy systems.

2 Material and methods

2.1 Discrete choice experiment

We assessed public perceptions through assessing the most and least important attributes of marine energy installations for the public, using a form of discrete choice experiment termed best-worst scaling (BWS) (Louviere et al., 2015). BWS was developed by Louviere and Woodworth (1990) to extend Thurstone's Method of Paired Comparisons to elicit trade-offs between paired items (Thurstone, 1927). Like standard discrete choice experiments, in a BWS study, each participant is shown several choice sets comprising a subset of attributes. Each choice set typically presents four or five attributes and the participants are asked to select their "best" and "worst" attributes in each choice set.

2.2 Modelling framework

Our analysis of best and worst choices draws on random utility theory (McFadden, 1974). Following convention, we expressed latent utility (y) as having a deterministic component (β) and a stochastic element expressed through the error term (ε), which is assumed to be independently and identically distributed (IID) Equation 1. Terms are indexed over individuals (i), alternatives (m), and in the context of best ($s = 1$) or worst ($s = -1$) choices.

$$y^{*}_{ism} = \beta_m + \varepsilon_{ims} \tag{1}$$

We accommodated heterogeneity in both latent scale and preference classes through a scale-adjusted latent class (SALC) model, first proposed by Magidson and Vermunt (2007). The SALC model can be represented as separating heterogeneity in preferences from heterogeneity in error variance, although we noted that it is possible to rationalize the 'scale' effect as *correlation* in preferences (Hess and Train, 2017). While acknowledging this, for simplicity we refer to the 'scale' parameter. Separation of forms of preference and error variance is achieved by identifying latent preference classes (classes of people who differ in their preferences, indexed over c) as well as latent scale classes (classes of people with different error variance, indexed over d). Differences in error variance are described by a scale factor (λ_d), which identifies the amount by which the parameter estimates of one class must be rescaled to arrive at the preference parameters appropriate to another class (Magidson and Vermunt, 2007). Using this model, and similar to Rigby et al. (2015), we expressed the probability (π) of individual i selecting alternative m as the best choice, conditional upon being in preference class c and scale class d, as Equation 2:

$$\pi_{ism|cd} = \frac{exp[\lambda_d \beta_{mc}]}{\sum_{m=1}^{M} exp[\lambda_d \beta_{mc}]} \qquad s = 1 \tag{2}$$

The probability that an alternative m is chosen as worst is Equation 3:

$$\pi_{ism|cd} = \frac{exp[-\lambda_d \beta_{mc}]}{\sum_{m}^{M} exp[-\lambda_d \beta_{mc}]} \qquad s = -1 \tag{3}$$

The probability of selecting m_1 as the best and m_2 as the worst is given by Equation 4:

$$\sum_c^d P_{cd} \pi_{i,m_1,m_2|cd} = \sum_c^d P_{cd} \pi_{i,m_1|cd} \pi_{i,\, m_2|m_1,cd} \tag{4}$$

Where P_{cd} is the probability that an individual is a member of preference class c and scale class d. We assumed sequential selection of best then worst choices, which precludes the same alternative being selected as both best and worst. Membership of scale and preference classes is simultaneously modelled as a function of individual specific characteristics using a multinomial logit functional form (Greene, 2019) (Equations 5, 6):

$$P_{ic} = \frac{exp[z_i' \phi_c]}{\sum_{c=1}^{C} exp[z_i' \phi_c]} \tag{5}$$

$$P_{id} = \frac{exp[z_i' \varphi_d]}{\sum_{d=1}^{D} exp[z_i' \varphi_d]} \tag{6}$$

Where z_i is a vector of individual specific characteristics.

2.3 Attributes

Through focus groups and a literature review, we identified eight attributes of marine energy facilities that are likely to be of most concern to the Chilean public (Table 1). Three focus groups, each comprising eight participants, were conducted in the cities of Puerto Montt, La Serena, and Coquimbo. Participants were selected using purposive quota sampling to ensure variation in gender and age. During the discussions, participants were asked to identify and discuss the attributes they considered most relevant when evaluating the potential impacts of marine energy projects. The findings from these focus groups, together with the literature review, informed the selection of attributes included in the Best–Worst Scaling experiment.

Boudet (2019) proposed four critical areas influencing the public's energy preferences: technology, people, place, and process. Our eight attributes include each one of these areas. For example, "Cost" and "Visual impacts" are related to the first category, technology, which refers to how the public perceives various factors related to the specific energy technology, such as the visibility of the technology and its impact on energy pricing. The second area, people, refers to socio-demographic and individual factors that can influence energy perceptions, such as age, educational level, and

TABLE 1 **Attributes of marine energy tested in best-worst scaling methodology.**

Abbreviated name	Marine energy attribute
Cost	Not to pay more than what I currently pay for my electricity bill.
Marine fauna	The negative impact on marine fauna (e.g. fish, whales, dolphins, sea lions, crabs, snails) is minimized.
Participatory	The decision-making process is equitable and inclusive.
Compensation	There is compensation for the local community by the energy company.
Visual impacts	The visual impact on the marine and terrestrial landscape is minimized.
Project scale	Instead of one big project in a zone, they install small projects in various zones along the Chilean coast.
Marine activities	The impact on marine activities (e.g. fishing, surfing, swimming, etc.) is minimized.
Unpopulated areas	The marine energy installations are located in unpopulated areas.

grade of trust in government or industry. The third area, place, highlights how local context shapes public energy preferences, such as the "Marine activities" attribute. Finally, the process component refers to diverse options and aspects of decision-making in energy development as the "Participatory" attribute.

2.4 Survey design and implementation

We tested the relative importance of these eight attributes for the Chilean public using the previously described BWS format. The BWS framing was "Which of the following qualities of a project would be most important to you, and which would be the least important to you?". The design consisted of 6 versions, each with 6 choice sets, and each choice set contained 4 attributes. Each respondent saw one version, and the order that survey versions were administered was randomized (without replacement) to ensure even coverage. We generated the survey design using Sawtooth software (see Sawtooth Software 2020, p8 for a detail of the algorithm used).

To assess whether respondent's socio-economic characteristics help explain preference heterogeneity, we obtained information on respondents' gender (i.e., women and men), age (i.e., number of years), income, and education (see Table 2). The survey also assessed respondent's views towards and trust in energy providers and regulating institutions. We assessed "To what extent, if at all, do you trust the following organizations when providing information about energy subjects?" and "To what extent, if at all, do you trust the following organization linked with decision making in energy subjects?" For the first question, the media and organizations were: scientific publications, NGOs, internet, newspapers, TV and Radio, Ministry of Energy, social networks, local government, and energy companies. For the second question, the organizations were: NGOs, university scientists, affected communities (are those that have been directly affected by an energy project, either by its construction,

TABLE 2 Socio-economic characteristics of respondents (n = 1,197) interviewed in Chile regarding their preferences for attributes of marine energy installations.

Socio-economic characteristics		% (No. of respondents)	Chilean population %
Gender	Male	48.5 (580)	48.9
	Female	51.6 (617)	51.1
Age range	18 - 24	24.5 (293)	15.0*
	25 - 34	29.9 (358)	15.7
	35 - 44	18.1 (217)	13.7
	45 - 54	14.6 (175)	13.3
	55 - 64	8.8 (105)	10.8
	65 - 85	4.1 (49)	11.4
Education level	Incomplete primary education	2.3 (28)	28.2
	Primary education	3.4 (41)	
	Incomplete secondary education	7.2 (86)	22.7
	Secondary education	26 (311)	
	Incomplete tertiary education (higher education)	25.3 (303)	22.7
	Tertiary education	35.6 (426)	
Income range (CLP$)	0 - 150,000	3.1 (37)	92.4
	150,001 - 300,000	9.2 (110)	
	300,001 - 450,000	13.5 (161)	
	450,001 - 600,000	13.9 (166)	
	600,001 - 750,000	12.8 (153)	
	750,001 - 900,000	9.9 (118)	7.7
	900,001 - 1,050,000	7.2 (86)	
	1,050,001 - 1,200,000	6.3 (76)	
	1,200,001 - 1,350,000	3.8 (46)	
	1,350,001 - 1,500,000	4.3 (51)	
	1,500,001 - 1,750,000	3.8 (46)	
	1,750,001 - 1,900,000	2.8 (33)	
	1,900,001 - more	7.9 (95)	

* Dates from Chilean national census (Casen Survey 2017).
Results displayed are percentages with the number of respondents displayed in brackets.

installation, or operation), energy companies, regional and local governments, and the central government. Responses were recorded on a five-point Likert scale, where 1 indicated "no trust", and 5 indicated "total trust".

Our survey was administered in four regions of Chile: Coquimbo, Valparaíso, Los Lagos, and Magallanes. We chose these regions because they represent the four macro zones of Chile (North, Central, South, and Austral) and are the most populated coastal regions in each macrozone. The survey method was face-to-face, with nine survey administrators. In total, we administered 1,200 surveys distributed equally across the four Chilean regions (300 respondents per region). Sampling was conducted in urban areas, specifically in regional capitals (33.6% of the sample), municipal capitals (61.4%), and other relatively large localities (5.0%). This design sought to capture geographical heterogeneity across Chile's coastline rather than differences between types of settlements. Responses for income and education were recorded according to predetermined categories. For example, we included ten response categories for monthly income, varying from "less than $180 USD" to "more than $2,300 USD", with an option for "I prefer not to answer." We presented six education categories: 1: Incomplete elementary school, 2: Complete elementary school, 3: Incomplete high school, 4: Complete high school, 5: Incomplete professional education, and 6: Complete professional education.

3 Results

3.1 Respondents

We interviewed 1,200 Chilean citizens. After removing those who did not complete all 6 choice sets, or who had missing sociodemographic variables, we had a sample of 1,197. The gender balance in our sample is nearly even, with only slightly more females (51.6% of respondents). This gender ratio is consistent with the broader Chilean population (51.1% females, National Census 2017). However, the age in our sample is slightly skewed towards younger respondents, and towards individuals with higher incomes (see Table 2).

3.2 Public trust

Responses to the statement, "To what extent, if at all, do you trust the following organizations when providing information about energy subjects?" are shown in Figure 1a. The highest levels of trust ("trusted" or "totally trusted") are for information from scientific publications, nongovernmental organizations (NGOs), and information from the internet (57%, 44%, and 33% respectively). In contrast, the highest levels of distrust, are related to energy companies, regional government, the Ministry of Energy, and social networks (73%, 62%, 60%, and 54%, respectively). Responses to the statement, "To what extent, if at all, do you trust in the following organization linked with decision making in energy subjects?" are shown in Figure 1b. Highest public trust was for scientists working for universities and, to a lesser extent, in NGOs and affected communities (70%, 61%, and 57% respectively). On the other hand, the highest levels of distrust, are found towards the Ministry of Energy and energy companies with 71% and 72%, respectively.

3.3 Chilean marine energy preferences

We assessed several models of respondents' preferences for marine energy installations, each with different numbers of scale and preference classes (Table 3). According to CAIC and BIC model selection criteria, our optimal model is a two scale, five preference class model. Scale class 1 has 68% of the respondents, and scale class 2 has 32% of respondents. Preference class 1 is the largest class, with 49% of the total sample (see Table 4). Class 2 also accounts for a large share of respondents (23%), with classes 3–5 accounting for ~10% each. Results describing individual preference and scale classes show two dominant views towards marine energy installations (Table 5; Figure 2).

For the largest class, preference class 1, the most important attribute of marine energy installations is "Marine fauna" (negative impacts on marine fauna are minimized). Other important attributes for this preference class are: "Visual impacts" (the visual impact on the marine and terrestrial landscape is minimized) and "Participatory" (The decision-making process is equitable and inclusive). The attributes: "Cost" (not to pay more than what I currently pay for my electricity bill) and "Compensation" (there is

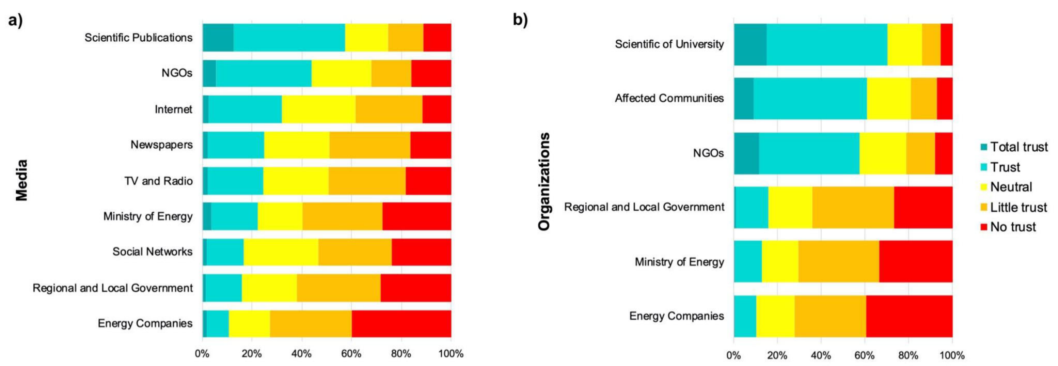

FIGURE 1
Public trust in **(a)** different sources of information: scientific publications, NGOs, internet, newspapers, TV and Radio, Ministry of Energy, social networks, regional government, and energy companies. **(b)** In different individuals or organizations linked with decision-making in energy subjects: scientists, communities, NGOs, regional government, Ministry of Energy, and energy companies.

TABLE 3 Model selection criteria for assessed scale adjusted latent class models of the Chilean public's preferences for the most important attributes of marine energy installations.

No. scale classes	No. preference classes	Log likehood (LL)	BIC(LL)	CAIC(LL)	No. parameters
1	1	-8484.96	17019.41	17026.41	7
1	2	-8053.19	16247.77	16267.77	20
1	3	-7940.88	16115.06	16148.06	33
1	4	-7842.51	16010.23	16056.23	46
1	5	-7755.96	15929.04	15988.04	59
1	6	-7709.08	15927.20	15999.20	72
2	1	-8244.02	16551.67	16560.67	9
2	2	-8022.65	16200.83	16222.83	22
2	3	-7884.73	16016.90	16051.90	35
2	4	-7809.05	15957.46	16005.46	48
2	5	-7723.93	**15879.11**	**15940.11**	61
2	6	-7682.15	15887.46	15961.46	74

Assessed models had 1 or 2 scale classes and 1 to 6 preference classes. The preferred model is a 2 scale class, 5 preference class model (indicated in bold).

compensation for the local community by the energy company) are the least important attributes for respondents in this class (See Table 1 for details of the attributes).

By contrast, the most important attributes of marine energy for preference class 2, the second largest class, are "Cost" and "Participatory". The least important attributes for this class are: "Visual impacts" and "Unpopulated areas". While preference classes 3 and 4 are most concerned about the "Project scale" (prefer small projects in various zones, instead of one big project) and their potential impacts on other "Marine activities", respectively. Finally,

TABLE 4 Multinomial logit model explaining membership of preference and scale classes from a scale-adjusted latent class model describing the Chilean public's (n = 1, 176) perceptions regarding the most important attributes of marine energy installations.

Variables	Descriptions	Class1	z-value	Class2	z-value	Class3	z-value	Class4	z-value	Class5	z-value
Intercept		0.80	1.96	1.84	3.72	-1.37	-1.89	0.07	0.09	-1.33	-2.12
Class size		0.49		0.23		0.10		0.10		0.09	
Covariates											
Income	Categorical (CLP/month)	0.11	0.90	-0.59	-3.04	0.04	0.18	0.67	2.93	-0.23	-1.09
Age	Years	-0.01	-2.92	0.01	1.83	0.01	1.57	-0.01	-0.84	0.00	-0.17
Education	Index 1-6 1 = primary (incomplete) 2 = primary 3 = secondary (incomplete) 4 = secondary 5 = tertiary (incomplete) 6 = tertiary	0.19	2.79	-0.34	-4.35	0.01	0.12	-0.16	-1.28	0.31	2.90
Confidence in information from the Energy Department	Likert scale none = 1: total = 5	0.04	0.56	-0.19	-1.88	0.27	2.35	-0.23	-1.49	0.10	0.96
Confidence in information from energy companies	Likert scale none = 1: total = 5	-0.09	-1.10	0.28	2.60	-0.10	-0.78	0.25	1.57	-0.34	-2.54
		Scale class 1	z-value	Scale class 2	z-value						
Intercept		0	.	-0.74	-1.74						
Scale class sizes		0.68		0.32							

TABLE 5 Results from effects-coded scale adjusted latent class model with 2 scale classes and 5 preference classes describing the Chilean public's (n = 1, 176) preferences regarding the most important (e.g., 'best') attributes of marine energy installations.

	Class 1		Class 2		Class 3		Class 4		Class 5	
Attributes	Coeff.	z-value	Coeff.	z-value	Coeff.	z-value	Coeff.	z-value	Coeff.	z-value
Cost (base case)	0.00	.	0.00	.	0.00	.	0.00	.	0.00	.
Marine fauna	5.37	10.22	-0.96	-4.86	4.47	5.32	3.91	2.13	4.80	6.41
Participatory	2.35	8.92	-0.85	-4.93	3.33	4.15	4.23	2.24	13.24	2.36
Compensation	0.17	0.75	-1.22	-6.77	0.54	0.61	1.93	1.09	-0.11	-0.16
Visual impacts	2.57	8.93	-2.42	-8.87	2.11	2.50	2.05	1.10	2.20	4.35
Project scale	0.43	1.72	-1.43	-6.73	5.23	5.91	2.37	1.30	0.66	1.30
Marine activities	1.14	4.93	-1.58	-6.82	2.29	3.04	5.33	2.88	0.80	1.67
Unpopulated areas	1.87	7.73	-3.22	-8.37	1.35	1.63	2.97	1.56	0.60	1.12
Scale Model				Scale parameter						
Scale class 1	0.00	.		1.00						
Scale class 2	-1.07	-5.14		0.34						

for the smallest class, preference class 5, the most important attribute of marine energy installations is "Participatory". Note that results in Table 5 are normalized relative to the attribute: "Cost" (i.e., the weight associated with installation costs is set to zero).

Results of a multinomial logit (MNL) model to assess determinants of belonging to a class show that income, age, education, and trust in information from the ministry of energy and energy companies, significantly predict class membership (Table 4). These results show that respondents in preference class 1 are significantly (α=0.05) more likely to be younger and with higher education levels. By contrast, respondents in preference class 2 are significantly more likely to have less education, lower-income and are more likely to trust information from energy companies.

Concerning the other respondents, members of preference class 3 are more likely to be younger and to trust information from the Ministry of Energy but not from energy companies. By contrast, members of preference class 4 are more likely to have more income and trust information from the energy company but not from the Ministry of Energy. Finally, members of preference class 5 are more likely to have more education but less income and distrust information from the energy company; in preference classes 4 and 5, the variable age is not associated with class membership.

4 Discussion

Marine energy encompasses various ocean energy technologies, such as waves, tides, (floating) wind, temperature and salinity gradients, and biomass. This paper focuses on the most promising for Chile: tidal and wave energy. Here we use a novel approach to explore heterogeneity in the preferences of civil society towards marine energy developments. One of the key findings is that our sample revealed substantial heterogeneity in public preferences for attributes of marine energy projects. We identified five groups of respondents within our sample who shared similar preferences and two-scale classes. Furthermore, respondents' socio-demographic characteristics and factors like trust in information from energy-related organizations significantly explain preference class membership. Our findings emphasize the need to account for preference heterogeneity in developing strategies to co-construct social and ecologically sustainable marine energy systems.

Our results provide an important overview of public preferences for eight attributes of marine energy projects. Results show that the "Marine fauna" attribute (the negative impact on marine fauna is minimized) plays a critical role in all preference classes, but there are differences in their effect. For example, this attribute was chosen most in preference class 1 (more likely to be younger, with more education, and are more likely to distrust information of energy companies). Moreover, it was the second most chosen in preferences classes 3 and 5, and third in preferences classes 2 and 4. With this evidence, one could argue that marine fauna protection should be a priority if industry or government want to obtain positive attitudes toward marine energy projects among the Chilean public.

These results coincide with Bergmann et al. (2006), who studied the acceptability and preferences toward different renewable energies. Their results indicate that despite heterogeneous preferences regarding the different attributes and technologies evaluated, reducing impacts on wildlife was the second most valued attribute. Similarly, Dreyer et al. (2019) studied resident stakeholders' positive and negative views of tidal power. Again, one of the main concerns included harm to marine life. Despite the limited deployment of marine energy, there is some empirical evidence of its effects on ecosystem change and biodiversity. Several studies reported that the displacement of marine species and the reduction of the marine water quality might be consequences of the operation of a tidal or

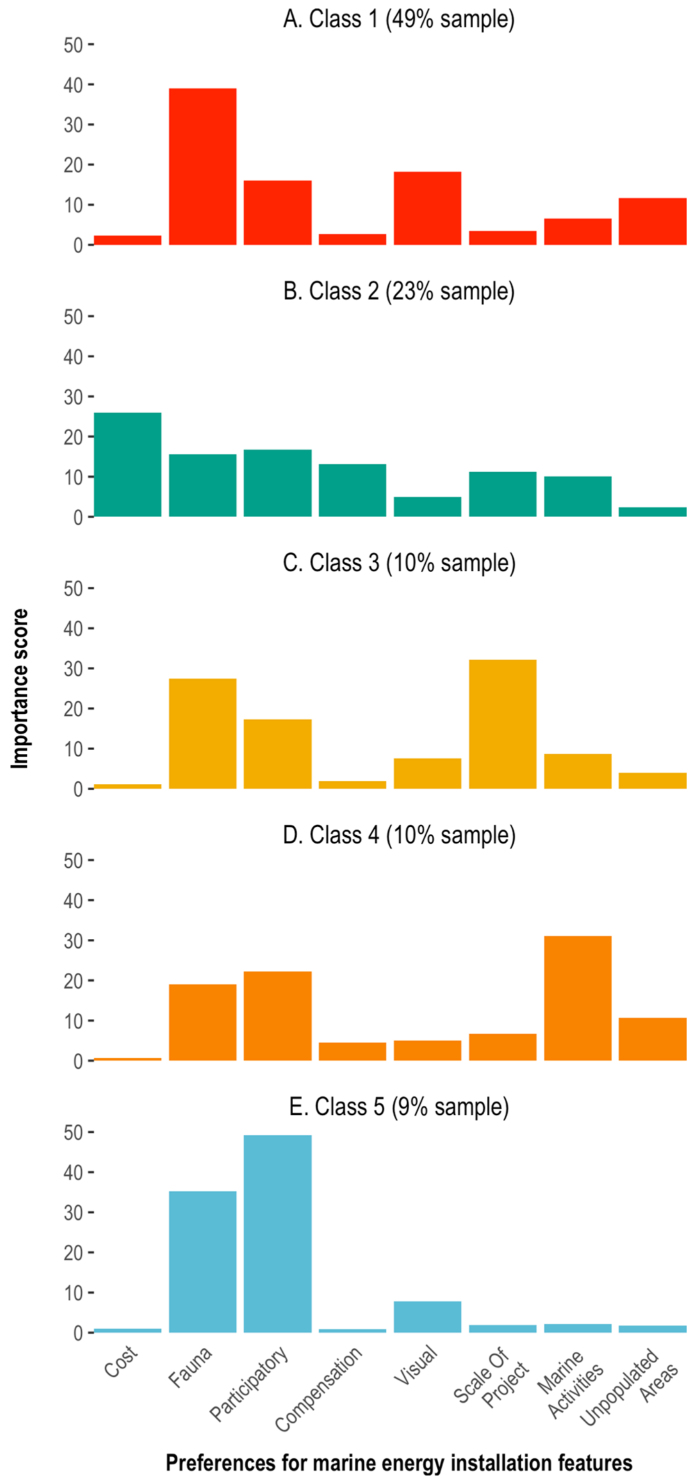

FIGURE 2
Importance scores describing the most important attributes of marine energy installations for the Chilean public (n = 1,197). Panels **(A–E)** represent preference Classes 1–5, respectively; the percentage in brackets indicates the relative size of each class.

wave power plant (Broadhurst et al., 2014; Wolf et al., 2009). Regarding habitat loss and fauna impacts, there is evidence that marine mammals often avoid areas of underwater construction, particularly piling, only slowly returning after construction is finished (Hammar et al., 2017; OEERA, 2008). In this line, perceived environmental impacts have been reported as critical barriers to the proliferation of marine energy projects (Bonar et al., 2015; de Groot and Bailey, 2016).

Our results show that "Cost" was the most important attribute for preference class 2 (respondents more likely to have fewer education years, lower income, and trust information from energy companies). By contrast, this attribute was the least chosen attribute for preference classes 1, 3, and 4, who are most likely to be young and high-income earners. This preference: "Not to pay more than what I currently pay for my electricity bill", is consistent with the results of Dreyer et al. (2019); where respondents' primary concern (in Washington, USA) was how increased electricity rates could have unequal or unfair outcomes. For example, a respondent said: "Tidal energy would be a great addition to the energy grid with one caveat; is it economically feasible? A wealthy person would think nothing of $30.00 to their electricity bill, but to a poor person, this could be a major expense". This argument is especially relevant if we consider the differences in the distributions of wealth, income, assets, and debt between a developing economy, Chile, and a developed economy, the United States (Bauducco et al., 2019).

In Chile high energy prices are an important concern, with 21% of population highlighting this as the main problem in the energy sector (Ministry of Energy of Chile, 2017). Unfortunately, in the current structure of energy markets, marine energy prices cannot compete with established technologies (Proimakis et al., 2021). Astariz et al. (2015) calculated the Levelized cost of marine energy, an economic indicator of the ratio between the total lifetime costs of an energy project and the total expected results, expressed in equivalent present value. The Levelized cost calculated for wave, tidal, and offshore wind energy was: €325/MW h, €190/MW h, and €165/MW h. In contrast, for example, onshore wind energy has an estimated levelized cost of €67.68/MWh (Allan et al., 2011; Astariz and Iglesias, 2016). Thus, regarding this attribute, economic support and the creation of government subsidies could mitigate one of the main barriers to developing the marine energy industry in Chile. Understanding preference structures such as the ones reported in this study, could help establish where these subsidies could be implemented better.

Understanding heterogeneity in preferences can improve our understanding of alternative innovation avenues. For example, preference class 3 prioritize smaller projects ("Project scale" attribute). Roberts et al. (2016) suggest that relatively little consideration has been given to exploring the potential of smaller-scale tidal power from more diverse locations and closer to populated areas. This could help make it more appealing for coastal communities since socio-environmental impacts are likely to scale with project size.

Regarding other critical aspects, the "Participatory" attribute (equitable and inclusive decision-making processes) was the most chosen by preference class 5, it was the second most chosen in preferences classes 2 and 4, and third in preferences classes 1 and 3. However, the Chilean environmental impact assessment system (SEIA) has long been criticized for not solving historical problems related to social, indigenous, and environmental fragilities (Agostini et al., 2017). For example, Ureta (2017) analyzed the case of a participatory policy carried out by the Ministry of Energy. The results show that this "participatory turn" in Chilean energy policy needs policymakers to radically change their notions of what public participation is, who is involved and what can be expected from them. Accordingly, international experiences highlight that governance issues are one of the main challenges of transitioning toward sustainable energy futures, especially with marine energy sources (Lange et al., 2018; Wright, 2015; Wright et al., 2016). Therefore, for marine energy to become a concrete option despite preference heterogeneity, it will be necessary to support and ensure participatory processes.

Our findings regarding trust are also relevant for interpreting these results. In Chile, several large-scale energy projects have generated prolonged public conflict and controversy over environmental impacts, procedural fairness, and public participation (Schaeffer, 2017; Delamaza et al. 2017; Agostini et al., 2017; Vallejos-Romero et al., 2016). These experiences have contributed to persistent concerns regarding the transparency and legitimacy of energy decision-making processes, which may help explain the high levels of distrust toward both energy companies and the Ministry of Energy observed in our study. Consequently, moving beyond consultation toward earlier, more meaningful, and potentially binding forms of public participation may be essential for building legitimacy and social acceptance of future marine energy developments.

This study has some limitations that should be considered when interpreting the findings. Although our sample broadly reflects the Chilean population in terms of gender and geographical coverage, younger, higher income, and more highly educated individuals are somewhat overrepresented. This sampling imbalance may affect the estimated prevalence of specific preference classes. For example, because membership in Preference Class 1 is associated with younger age and higher education levels, the relative size of this group may be overestimated compared with the broader Chilean population. Consequently, the proportion of respondents assigned to this class should not be interpreted as a nationally representative estimate. However, the primary objective of this study was to identify patterns of preference heterogeneity and their socio-demographic correlates rather than to estimate the prevalence of each preference class in the Chilean population.

5 Conclusion and policy implications

This study identified five groups of respondents based on their main preferences towards marine energy developments. The most critical attributes of marine energy projects varied significantly among groups, but three attributes were dominant: "Marine fauna", "Cost", and "Participatory". These differences indicate distinct values and world views that structure Chileans' perceptions of the marine environment and its use as a source of energy. Considering our results, it would be important to promote research on the impacts on marine fauna. Likewise, it is a priority to address concrete ways to mitigate the potential economic impacts on the associated communities, especially those with fewer resources. Furthermore, Chile should move from consultation to participation in decision-making to promote a more transparent and collaborative participatory process, as these can shape public perceptions of new energy technologies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Comité de Ética de la Pontificia Universidad Católica de Chile. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

BG: Formal analysis, Investigation, Project administration, Visualization, Writing – original draft. RE: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. VE: Investigation, Project administration, Visualization, Writing – review & editing. MB: Data curation, Methodology, Validation, Visualization, Writing – review & editing. CR-C: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. FV-L: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing. RP: Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. SN: Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. KD: Data curation, Investigation, Methodology, Supervision, Visualization, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Software, Validation. SG: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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