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# Renewable gases in the heating market: Identifying consumer preferences through a Discrete Choice Experiment

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ABSTRACT

Renewable gases like biomethane or Synthetic Natural Gas (SNG) can play an important role in short-to mid-term decarbonization of the residential heating sector. By (partially) replacing the dominant natural gas, they accomplish two major goals: lowering $CO_2$ emissions and lessening import dependencies. While existing research points to great production potential and technical options for producing renewable gases, the demand side has largely been neglected. Yet consumer decision making is highly relevant for climate change mitigation. Against this backdrop, we conducted a Discrete Choice Experiment with 512 heating consumers in Germany, a country with a high dependency on natural gas. We decomposed the gas tariff into six attributes (share of renewable gas, labels, regionality, biomethane feedstock, supplier type, and price) with varying attribute levels.

We identified knowledge gaps regarding both biomethane and SNG technologies, gaps which are more pronounced for SNG. Results show that the gas mix and the price are key in consumer evaluations. Labels and feedstock are less relevant, regionality and supplier type almost neglectable. Biomethane is clearly favored over SNG, which comes as a surprise given the past controversy over food vs. fuel. Our results call for raising consumer awareness and standardizing information in order to improve decision-making.

## 1. Introduction

Consumers and their demand for goods and services play a critical role in climate change mitigation. Private consumption directly and indirectly drives resource consumption and emissions (Herbes, 2021), while consumer demand also influences technology development and market landscapes (Chen et al., 2021). The daunting challenge of climate change calls for "… a fundamental change in existing systems of production and consumption and energy use …" (Jensen et al., 2018: 297). Especially important to this change is private demand for energy, making greening energy demand through renewable energies an important approach towards mitigating climate change.

In its Climate Target Plan the EU Commission plans to cut its greenhouse gas emissions by at least 55% (compared to 1990) by 2030 to pave the way for climate neutrality by 2050 (European Commission, 2021a). This overall target is backed by the Renewable Energy Directive II (RED II) which establishes a binding target of 32% renewable share by 2030, which has been increased to 40% (European Parliament and Council, 2018; European Commission, 2021b). Of the three target sectors (electricity, transport, heating and cooling) heating is clearly not on track towards 2050 (Braungardt et al., 2021). In Germany, for example, in 2021, the target value for decreasing $CO_2$ emissions from the building sector was missed for a second year in a row, making it the only sector not to meet its target share (Hein et al., 2022).

Generally, residential heating accounts for more than a quarter of the final energy demand in the EU (European Commission, 2021a; European Parliament and Council, 2018) and is still largely based on imported fossil fuels (Bertelsen and Vad Mathiesen, 2020). Natural gas remains the main energy source for generating heat in buildings in many European countries, e.g. Germany, Netherlands, Belgium or Italy (Braungardt et al., 2021; Eurostat, 2020). The debates revolving around the Russian invasion of Ukraine (e.g. finding new sources of natural gas), as well as the initiative by the European Commission to consider natural gas to be "sustainable" (European Commission, 2022), demonstrate that

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methane will continue to play a major role in the EU energy system in the mid- to long-term.

How can a methane-dependent heating sector be decarbonized through renewables in order to mitigate climate change? Here, we study two approaches. The first and most common is biogas that has been upgraded to biomethane and can be injected into the public gas grid (Scarlat et al., 2018; European Biogas Association, 2020). The second and more recent approach to increasing the renewable share in the gas grid is the so-called Power-to-Gas (PtG) technology, by which surplus electricity from renewable sources is used to produce hydrogen through electrolysis (Winquist et al., 2021). One of the end products is Synthetic Natural Gas (SNG), which, like biomethane, can replace natural gas (Winquist et al., 2021; Götz et al., 2016; Horschig et al., 2018; Ueckerdt et al., 2021; Gätsch et al., 2022). While biomethane can be considered the more established technology, PtG technologies are developing quickly, making SNG a viable option for the mid-term (European Biogas Association, 2020; Winquist et al., 2021; Ueckerdt et al., 2021; Gätsch et al., 2022). A potential third option is hydrogen, which also stems from PtG but without methanation. However, its use in the existing transport and heating infrastructure is limited and therefore it is not a short-term option. Neither biomethane nor SNG has gained more than a marginal share of renewable gas in the European gas grid (Scarlat et al., 2018; Herbes et al., 2021). However, there are analyses of the potential for biomethane production in Europe, ranging from 17 billion cubic meters (as realistic and sustainable scenario) to 35 billion cubic meters (European Commission's new target) (Abdalla et al., 2022). Both (biomethane and SNG) offer considerable benefits over natural gas regarding global warming potential: While burning natural gas emits fossil $CO_2$, biomethane stemming from renewable sources (i.e. manure or energy crops) and SNG stemming from surplus electricity from renewable sources (i.e. wind or PV) and a $CO_2$ sink (like a biogas upgrading plant) emit considerably less fossil $CO_2$ (Scarlat et al., 2018; Winquist et al., 2021; Götz et al., 2016; Horschig et al., 2018). For an overview and comparison between technologies, especially taking into account different system boundaries and conditions, please see Kolb et al. (2021) and Vega Puga et al. (2022). Just like natural gas, renewable gases for household consumers in Germany are provided through the public gas grid and are offered by energy suppliers who often also offer other services like electricity (Herbes et al., 2021).

Biomethane offerings to private heating customers today, especially in Germany, are driven by legal obligations on the customer side and the volume of biomethane that goes into this application is much lower than the volumes going into electricity production and the transportation sector. Herbes et al. (2021) identified 127 different biomethane offerings for end customers in their comparative international study. Voluntary use driven by consumer demand offers great untapped potential. If we consider consumer demand for renewable energies key to tackling climate change, understanding consumer preferences and their subjective logics, especially for renewable gases, becomes central. However, we know very little about these preferences and logics.

Instead, existing research is dominated by technological and engineering analyses (Krupnik et al., 2022). Some research has shown biogas ranks lower in popularity for renewable electricity than solar or wind (Wang et al., 2019; Danne et al., 2021), or even other biomass-based technologies (Zhao et al., 2018). Research on marketing biomethane has focused on the supply side (Herbes et al., 2016, 2021), with little focus on the demand side, although Fonseca et al. (2019) have already called for studies on the social and political issues of energy systems including hydrogen.

Forsa (2012) and Herbes et al. (2018a) found consumers preferring waste-based biomethane products over energy crop-based gas; they also identified cost sensitivities and found consumers poorly informed about biomethane. Moreover, in France, Herbes et al. (2018a) showed preferences for local production, small suppliers and eco-labels, in line with results from research on renewable electricity products.

Directly related to our study is that of Rilling and Herbes (2022), who performed 22 qualitative interviews with heating consumers, complemented by interviews and focus group discussions with 27 experts on biomethane and SNG. They confirmed knowledge gaps and low involvement as well as the importance of costs. The importance of regionality and the gas provider in a tariff also surfaced.

Most intriguingly, the interviews indicated changes in consumer perception: The overwhelming criticism of biogas linked to the use of energy crops seemed to have subsided, and biogas questions solicited numerous neutral and positive statements. This study was also the first to explore consumer perceptions of PtG and SNG. Not surprisingly, there was little awareness of these technologies, prompting neutral evaluations at first. But informed that PtG can use surplus electricity from renewable energy plants and $CO_2$ from biomethane plants, most interviewees changed their evaluations to positive.

Given the potential in channeling renewable gas into the voluntary private heating market, as well as the predominantly qualitative approach of previous research to consumer preferences, we raise the following research questions:

(1) Which product attributes are important to consumers in the renewable gas for heating market and how important are these attributes?
(2) How do preferences vary by different consumer groups?

Our study was situated in Germany with its strong biogas sector. This sector has undergone several fundamental legislative changes that add to the relevance of this study, as the sector needs new business models that go beyond producing electricity from biogas. Upgrading and injecting biomethane into the existing gas grid is one viable option (Winquist et al., 2021).

Our results should be applicable in other countries with an existing and developing biomethane market, e.g. Switzerland, the UK, Austria, or South Korea as laid out by Kim et al. (2020) and Herbes et al. (2021) or countries highly dependent on natural gas in the heating sector (Bertelsen and Vad Mathiesen, 2020; Eurostat, 2020).

The article unfolds as follows: In Section 2, we explain our research design, the choice experiments we conducted as well as some descriptive statistics. In Section 3, we present the results of the experiments. In Section 4, we discuss these results and conclude with our findings in Section 5.

## 2. Material and methods

Our approach to eliciting preferences for renewable gases in the heating market is based upon a Discrete Choice Experiment (DCE) implemented through an online survey. Using the data generated from the experiment, we determined preferences and their differences across consumer segments.

### 2.1. Discrete Choice Experiments

DCEs as an approach to measuring stated preferences (Adamowicz et al., 1994) have evolved into a central tool for measuring consumer preferences in both research and practice. Beyond their use in marketing research, they have found application in a wide range of fields, from analyzing preferences for nonmarketable goods and services (Rakotonarivo et al., 2016, 2017) to soliciting responses to different policies (Narjes and Lippert, 2016; Ščasný et al., 2017; Aruga et al., 2021; Walter et al., 2023; Kanberger and Ziegler, 2023; Odland et al., 2023; Moon et al., 2023).

So it is no surprise that DCEs have also found their way into research on renewable energy, especially on renewable electricity, where researchers have investigated consumer decisions about renewable electricity tariffs (Danne et al., 2021; Boeri and Longo, 2017; Tabi et al., 2014; Borriello et al., 2021; Knoefel et al., 2018; Kalkbrenner et al., 2017; Rommel et al., 2016). DCE research related to renewable gases is scarcer, used to analyze farmers' decisions about investing in biogas (Zemo and Termansen, 2018) or their calculus around different substrates (Sauthoff et al., 2016). Several studies have also been conducted on the marketing of soil and fertilizers from biogas residues to consumers (Herbes et al., 2020a; Dahlin et al., 2016, 2019). However, this study is the first to use a DCE in a European context to investigate consumer preferences for renewable gases in residential heat generation.

### 2.2. Experimental design

Given the novelty of our research topic, we opted for an open approach in the first step of our design. This comprised 22 interviews with heating consumers followed by a qualitative content analysis (Rilling and Herbes, 2022). The results were supported by a broad literature review on willingness-to-pay (WTP) and DCE in the renewable energy sector, e.g. Herbes et al. (2016), Kim et al. (2019, 2020), Kowalska-Pyzalska (2019), Herbes et al. (2015), Oerlemans et al. (2016) and Sagebiel et al. (2014). From this, we identified the relevant product attributes and their levels displayed in Table 1.

The first attribute, Gas Mix, allows for many different product combinations using varying shares of different gas origins. After the analysis of biomethane offerings in Germany from Herbes et al. (2021), we decided to include only typical product combinations for biomethane and transferred those combinations to the options available for SNG products. Table A1 (see Appendix) summarizes these combinations.[1]

(Eco) labels, the second attribute, have been shown relevant for consumer decisions in the energy sector (see e.g. Knoefel et al., 2018; Herbes et al., 2020b; Kuhn et al., 2022) and were also highlighted by our interviews. That labels may not be well-known to consumers was identified by Rommel et al. (2016) in their analysis of consumer preferences for renewable electricity products. Building on this insight, we decided to include a *Fake* label besides two established labels (*TUEV* and *Green Gas Label GGL*) in our DCE. While the *TUEV* label guarantees a certain share renewable methane in the product, the *GGL* is a stricter label (e.g. regarding additional investments into new renewable projects) that is run by consumer and environmental associations. The labels are shown in Appendix A2. Furthermore, we included label combinations to account for potential effects of multiple labels for one product.

The third and fourth attributes capture the proximity of the production site (i.e. regionality) and the supplier type (i.e. its legal form). Both were found relevant in our interviews and our literature review (Tabi et al., 2014; Knoefel et al., 2018; Kalkbrenner et al., 2017; Kuhn et al., 2022; Fait et al., 2022). We tested three supplier types: cooperatives (citizen-managed energy providers, often operating regionally), municipal utilities (the dominant provider form in Germany -"Stadtwerke"- mostly also operating on a local scale) and large investor-owned energy corporations operating on a national scale. As the results from Kalkbrenner et al. (2017) indicate preferences for regionally generated electricity, we also included this attribute in our choice sets. In the DCE, regionality was defined as "… the proximity of your place of residence to the production facilities where the gas product is generated." and differentiated between regional and non-regional production.

The fifth attribute captures the influence of different feedstocks used to produce biomethane, as previous research has highlighted its relevance to consumers (Herbes et al., 2018a, 2021; Dobers, 2019; Schumacher and Schultmann, 2017), a fact confirmed by our interviews. We included three feedstock options -energy crops, waste, and a mix of both-in the choice sets for biomethane. For SNG products, the attribute was not presented, as SNG is not derived from feedstock.

The last attribute, price, is a central element in all WTP studies. We opted for an individual yearly price for each respondent as our base scenario. We asked all participants for their individual housing parameters (i.e. year of construction, refurbishment status and living space). Using the TABULA WebTool (2017) we calculated the individual annual energy consumption for heating. Which we then used to calculate an individual yearly price for the reference product of 100% natural gas. We manipulated the price for biomethane and SNG shares in the product using six different and increasing levels for each product, with the first level (no increase) being identical for all products. Details can be found in Table A3. The price(s) presented to participants were annual prices.

We carefully balanced the different attribute levels in our DCE against the number of levels effect: The knowledge about this can be traced back to the seminal work of Wittink et al. (1989). They explored the impact of the number of attribute level for ranges in attribute attractiveness ratings and regression coefficients ratings. Additionally, McCullough (1999) discovered that the number of levels effect can be attributed to respondents' tendency to evenly distribute their mental stimulus representations and responses across corresponding continua. On the other hand, Pinnell and Fridley (2001) observed that while there is no clear academic foundation for the number of levels effect, a distinction exists between quantitative and qualitative attributes. Qualitative attributes are minimally affected due to respondents' existing knowledge about the number of levels required to describe such attributes, which is based on everyday knowledge. In contrast, respondents tend to distribute their responses across the entire range for quantitative attributes. For quantitative attributes, we have utilized a range of five to six levels, while for qualitative attributes, we have employed a larger or smaller number of levels as appropriate. Consequently, the influence of the number of levels effect on our results should be negligible.

**Table 1**
Product attributes and attribute levels.

| Attribute | | Attribute Levels |
|---|---|---|
| **(1) Gas Mix** | **(1.1) Biomethane Share** | 0% |
| | | 5% |
| | | 10% |
| | | 50% |
| | | 100% |
| | **(1.2) SNG Share** | 0% |
| | | 5% |
| | | 10% |
| | | 50% |
| | | 100% |
| | **(1.3) Natural Gas Share** | 0% |
| | | 50% |
| | | 90% |
| | | 95% |
| | | 100% (Reference Product) |
| **(2) Labels** | | No label |
| | | TUEV |
| | | GGL |
| | | Fake |
| | | TUEV + GGL |
| | | TUEV + Fake |
| | | GGL + Fake |
| | | TUEV + GGL + Fake |
| **(3) Regionality/Proximity of production sites** | | Not Regional |
| | | Regional |
| **(4) Supplier Type** | | Energy corporation |
| | | Municipal utility |
| | | Cooperative |
| **(5) Biomethane Feedstock** | | Energy crops |
| | | Waste |
| | | Mix of energy crops and waste |
| **(6) Yearly Price** | | → Various product-specific price increases (from 0 to 904%); see Table A3 |

[1] To ease reading, we will refer to the products only by their renewable share: e.g. 'BM: 5%' indicates a gas mix of 5% biomethane and 95% natural gas, 'SNG: 10%' accordingly a SNG share of 10% and 90% natural gas.

Fig. 1 shows an exemplary choice set from the online survey. In total, respondents were asked to complete 11 choice sets, where four product alternatives were shown, as well as the reference product as an opt-out option. We collected 523 complete responses, for a total of 5753 active choices. However 11 cases had to be removed from further analysis due to complete random answer behavior, leaving us with 512 complete cases and accordingly 5632 choices for further analysis.

The experimental design was generated with the R-package idefix to obtain a Bayesian optimal design. To group the concepts into choice tasks we used the SAS ProcOptex Macro to build 100 D-optimal versions for the questionnaire (Kuhfeld et al., 1994; Traets et al., 2020). Analysis of the DCE data was done using Sawtooth software.

The DCE was embedded in a larger survey covering further aspects like information on the current gas tariff, knowledge about biomethane and SNG, sociodemographic information, as well as attitudes towards different financing options for renewable gases.

### 2.3. Data collection

After ten iterative think-aloud pretests with potential participants, we shortened the length of the questionnaire to reach a final average interview duration of approximately 17 min (including a 4:46 min video). Data collection was carried out in collaboration with Kantar Profile Network, allowing access to 3,700,000 panelists worldwide and providing a representative sample of Germany. To participate in our survey, panelists had to be at least 18 years old, use natural gas for heating at home, and have decision-making authority in their household over the gas provider and the corresponding tariff.

The soft launch of the survey took place at the end of May 2021. After 55 responses were checked for survey duration, data quality and completeness, we moved on to the main survey, which we ended on June 10th' 2021 with 523 responses.

Our interviews, like previous studies (Herbes et al., 2018a; Forsa, 2012), revealed knowledge gaps among consumers regarding biomethane and its production. Given the relative novelty of SNG, we anticipated even wider gaps regarding its production. To tackle this issue and improve validity of the choice experiment (Schläpfer and Fischhoff, 2012), we produced an explanatory video to be watched as prerequisite to completing the survey. That video can be found here. It contained information on each of the three tested gases (natural gas, biomethane and SNG), their production, $CO_2$ emissions and their supply. It was included in the survey before the DCE (to ensure sufficient knowledge) but after the questions regarding pre-knowledge.

### 2.4. Estimation methods

The DCE was analyzed by a so-called multi-method approach, a set of techniques to explore heterogeneity in the data and find the best estimates for explaining respondent preferences. First, an aggregate Logit-model was used to describe the average preferences of the sample. Second, a latent class model was estimated to find meaningful homogenous preference-based segments. Assuming a higher heterogeneity than captured by the latent classes, a Hierarchical Bayes (HB) multinomial logit (MNL) was estimated to capture the heterogeneity on an individual level. Analyzing the HB-MNL utilities, we found that the latent class segments are represented in the HB estimates, but shrank somewhat to the population mean. This is related to the assumption of a multivariate normal distribution on which is based the HB-MNL. The final analyses were based on a combined approach, with separate HB-models for each latent class. This allows using a distribution-independent first stage to estimate the segment membership of the respondents, and then capturing the within-class heterogeneity by estimating individual utilities. For the analysis in this paper, we use a generic model with main effects only (Hein et al., 2020; Louviere et al., 2010; Orme, 2010; Rossi, 2014; Rossi et al., 2005).

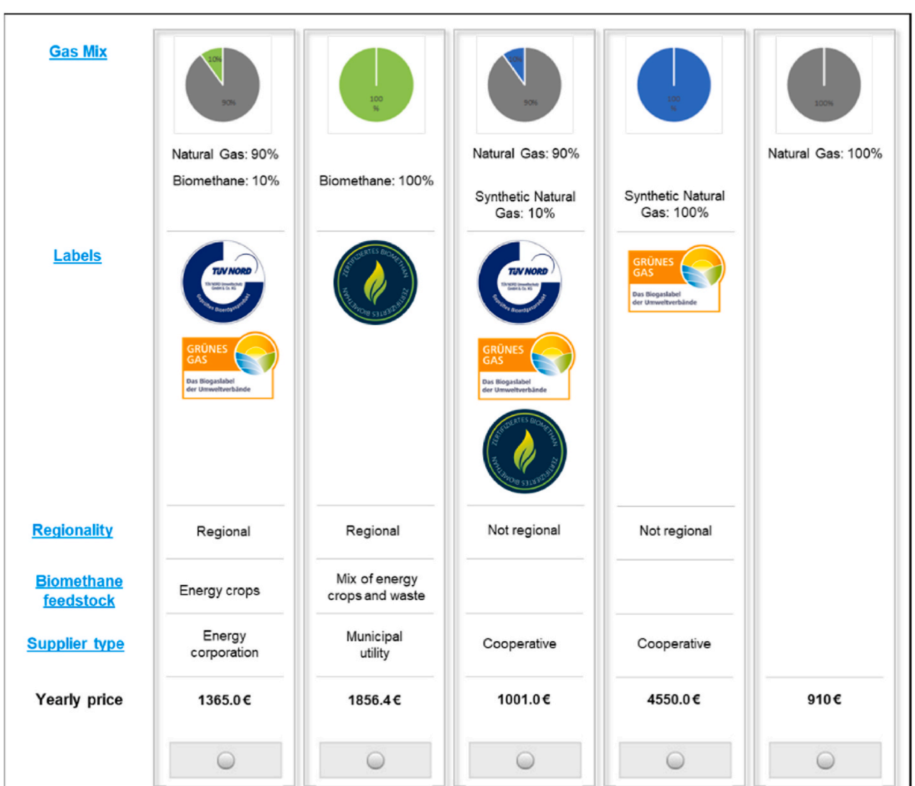


**Fig. 1.** Exemplary choice set (translated from German and visualized by authors).

### 2.5. Sociodemographic variables

To further guide our analysis, we captured the sociodemographic variables presented in Table 2, showing our sample values compared to national averages from federal data.

Besides this sociodemographic information we also added items related to environmental behavior: We found a large share of respondents sourcing renewable electricity in their homes (42.4%) compared to the national average (17.9%). This is a good indication of the relevance of our sample, because both products (electricity and gas tariffs) have aspects in common: low involvement (Fait et al., 2022; Friege and Herbes, 2017), invisible consumption (Herbes and Ramme, 2014) and complex, sometimes confusing tariff offerings (Rilling and Herbes, 2022; Fait et al., 2022).

## 3. Results

Reviewing the residential heating context of our respondents and their knowledge regarding the two underlying technologies, Table A4 (see Appendix) shows that almost half of the respondents live in buildings that are more than 38 years old. More than 2/3 of the buildings built before 2010 are only partially renovated (i.e. no longer in original condition, but not yet up to date with the latest energy-saving regulations). The average (calculated) annual heating costs for all respondents (in all residences) are approximately 850€ which is in line with a representative statistic from 2021 (Heizspiegel, 2022), which shows that the range of heating costs for an average 70-square-meter apartment with central gas heating in the billing year 2021 was between 545 and 1185€. On average it was 820€.

For the larger share (almost 60%) of our respondents, biomethane is still unknown as a potential natural gas substitute for their heating system. Of those familiar with biomethane, 20% have already opted for a biomethane tariff, which is about 9% of all respondents. Interestingly, this decision was motivated strongly by legal obligations. More than 60% of those sourcing biomethane named the fulfilment of a legal obligation from heating law as their main reason.

Fig. 2 shows the self-assessed knowledge about the functionality of a biogas and PtG plant (before watching the explanatory video): We see that respondents claimed only modest knowledge of biogas technology, yet even this was clearly higher than that of PtG technology.

**Table 2**
Sociodemographic information.

| Variable | Values | Sample | National average | Source |
|---|---|---|---|---|
| **Sex (n = 512)** | Female | 39.6% | 50.7% | FSO (2021a) |
| | Male | 60.2% | 49.3% | |
| | Diverse | 0.2% | N/A | |
| **Age (n = 503)** | Mean | 42.19 | 44.5 | FSO (2020a) |
| **Household income (net, n = 512)** | Less than 1000€ | 6.4% | 9.7% | FSO (2021b) |
| | 1000-1999€ | 16.2% | 26.3% | |
| | 2000-2999€ | 26.2% | 23.7% | |
| | 3000-3999€ | 21.3% | 16.2% | |
| | 4000–4999 | 14.5% | 10.4% | |
| | 5000€ and more | 10.2% | 13.7% | |
| | No answer | 5.3% | N/A | |
| **Highest educational achievement (n = 511)** | No formal education | 3.1% | 16.3% | FSO (2020b) |
| | Still attending school/vocational training/studying | 8.0% | 8.9% | |
| | Finished vocational training | 41.9% | 46.6% | |
| | Master craftsman training/ vocational school | 13.7% | 9.3% | |
| | Bachelor degree | 9.8% | 2.6% | |
| | Diploma, Master or PhD degree | 23.5% | 15.9% | |
| **Purchase of renewable electricity at home (n = 512)** | Yes | 42.4% | 17.9% | FSO (2019) |
| | No | 43.2% | 82.1% | |
| | Unknown | 14.5% | | |

### 3.1. Hierarchical Bayes estimation: mean utility values and attribute importance

Table 3 shows the estimated mean utilities for the HB model. The values are only to be compared within one attribute and sum to zero within this attribute. In the case of binary choices (e.g. regional vs. non-regional), the correct interpretation is that one level is preferred over the other. A negative value, however, does not mean that the choice is considered unattractive. In the case of three or more levels (e.g. labels), the level with the highest value is, ceteris paribus, preferred (Dahlin et al., 2019; Orme, 2010). For example, based on the data shown under the label attribute, we can conclude that a product with all three labels is preferred over a product with only one label.

The comparatively high standard deviations can be attributed to the high heterogeneity of the data set, discussed in the next section. Comparisons of utility values between attributes is not possible, but only between levels within the same attribute. Only the range of the utility values within each attribute can be used to get an impression of the relative importance of the different attributes.

Therefore, the yearly price and the gas mix are to be considered as the two most important attributes to consumers. Reporting and interpreting utility values for the opt-out-option does not make sense here (Johnson, 1989), but we can conclude from the 904 times this option was selected that the regular natural gas product is favored over the other products in 16.05% of the choices – which is in line with other studies (Chwalek et al., 2018) and no surprise for rather new technologies.

Looking at the model statistics, we see that with a McFadden Pseudo R-Squared of 0.62, our model performed well. This is also indicated by the Root Likelihood (RLH) value of 0.55, a level 2.75 times greater than the null likelihood value (in the case of complete randomized choices between five product alternatives) of $1/5 = 0.2$. Therefore we conclude that our model fits the dataset well (Sawtooth Software, 2021a; Côté et al., 2022).

Taking this further, we can analyze the relative importance of each attribute for the total utility of a product. The ranges within attributes' utility values (highest minus lowest value) add to 100 per cent and therefore indicate the importance of each attribute. Table 4 displays the according results:

Again, we see that the gas mix and the yearly price weigh most heavily in consumer purchasing decisions. At a relatively equal but decidedly lower level of relevance are labels and the biomethane feedstock, while supplier type and regionality can be considered as comparably unimportant.

### 3.2. Exploring preference differences between consumer groups

Analyzing choice-based data in more detail can be done using different consumer groups. This allows insights into and explanations of differences in preferences. One approach to segmenting consumer groups is based upon the data generated from the choice experiment itself, i.e. the individual part worth utilities. This way, respondent segments with homogenous preference structures can be identified and these segments are called latent classes (see e.g. Tabi et al., 2014; Dahlin et al., 2016; Sawtooth Software, 2021b). This approach builds upon the Sawtooth software and its latent class module (Sawtooth Software, 2021b). However, our data, especially the model fit indicators, showed high heterogeneity. Segmenting (=homogenizing) the sample into latent classes would not have made sense in this case, as it would have neglected the identified heterogeneity. Instead, we opted for an

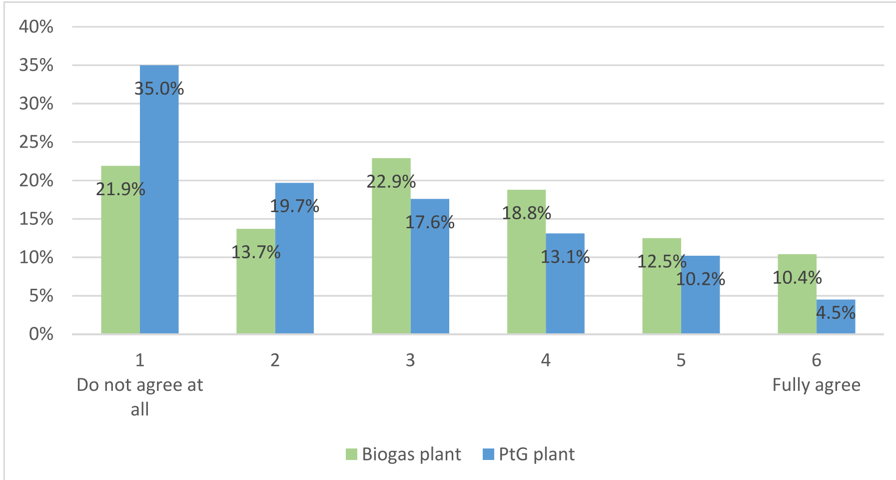


**Fig. 2.** Self-assessed knowledge about the functionality of a biogas and PtG plant ('I know how a biogas/PtG plant works'; n = 512).

**Table 3**
Mean utility values from the HB model, Standard Deviations (SD) in brackets. *An interpretation of the prohibitions of feedstock (n.n.) would not have made any sense here. We therefore re-centered the three meaningful values around zero. The sum of values therefore does not equal zero.

| Attribute | Attribute Levels | HB Estimation Results (SD) |
|---|---|---|
| **Gas Mix** | BM: 5% | 23.4 (64.0) |
| | BM: 10% | 35.5 (51.1) |
| | BM: 50% | 18.3 (48.2) |
| | BM: 100% | −5.6 (50.4) |
| | SNG: 5% | 37.6 (55.7) |
| | SNG: 10% | 22.3 (47.1) |
| | SNG: 50% | −11.0 (48.9) |
| | SNG: 100% | −42.2 (61.1) |
| | BM: 50%, SNG: 50% | −78.4 (67.3) |
| **Labels** | No label | −15.4 (47.1) |
| | TUEV | −7.1 (45.8) |
| | GGL | −9.7 (44.6) |
| | Fake | 2.4 (45.3) |
| | TUEV + GGL | −4.3 (45.0) |
| | TUEV + Fake | 12.3 (43.1) |
| | GGL + Fake | 6.5 (44.6) |
| | TUEV + GGL + Fake | 15.3 (46.5) |
| **Regionality** | Not Regional | −5.8 (20.8) |
| | Regional | 5.8 (20.8) |
| **Biomethane Feedstock*** | Energy crops | 2.55 (34.1) |
| | Waste | −2.55 (34.7) |
| | Mix | 2.45 (33.4) |
| **Supplier Type** | Energy corporation | −0.1 (26.5) |
| | Municipal utility | 0.5 (27.3) |
| | Cooperative | −0.4 (26.5) |
| **Yearly Price** | Level 1 | 98.1 (52.1) |
| | Level 2 | 24.0 (26.1) |
| | Level 3 | −5.9 (21.2) |
| | Level 4 | −21.7 (23.5) |
| | Level 5 | −39.6 (26.6) |
| | Level 6 | −55.0 (34.5) |
| **McFadden Pseudo R-Squared (Pct. Cert.)** | | 0.62 |
| **Root Likelihood (RLH)** | | 0.55 |
| **Average Variance** | | 3.97 |
| **Parameter RMS (root mean square)** | | 2.15 |
| **n** | | 512 |

alternative approach to explore preference differences between consumer groups, as in Côté et al. (2022). It is worth noting that HB-MNL models (as used in this study) are known to capture multimodal preference heterogeneity, obviating the need for specialized approaches (Goeken et al., 2023).

We used two variables from the data set to segment our sample. The first of these was whether or not respondents knew about the possibility of replacing natural gas with biomethane (=knowledge biomethane). The second was whether or not respondents source renewable electricity at home (=renewable electricity at home), a service which we consider comparable in many aspects to renewable gas consumption at home. We consider these two variables as key for explaining differences in preferences as they might weaken reservations towards the new technologies (knowledge) or serve as a proxy for climate change awareness and according behavior (renewable electricity). Table 5 shows the average utility values segmented in the two different ways.

**Table 4**
Attribute importance scores.

| Attribute | Importance Score |
|---|---|
| **Gas Mix** | 33.5 % |
| **Labels** | 16.1 % |
| **Regionality** | 5.1 % |
| **Biomethane Feedstock** | 13.5 % |
| **Supplier Type** | 6.3 % |
| **Yearly Price** | 25.5 % |

We also expected housing parameters to play an important role, so we segmented our sample following a two-step cluster analysis. Surprisingly, this did not uncover relevant differences between groups, and so those results are not presented here.

We also checked for differences in perceptions and preferences stemming from different educational levels. However, we did not find significant differences to report either.

Table A5 in the Appendix presents the sociodemographic as well as residential information of the different groups. Those knowledgeable about biomethane tend to be female, younger, better educated, wealthier and more inclined to opt for renewable electricity at home than those lacking biomethane knowledge. The group of those purchasing renewable electricity both overlaps and differs from the biomethane cognoscenti. Those purchasing renewable electricity tend to be male, wealthier, better educated and more often own the building they live in.

Each HB-estimation has an own scale factor, so it is not possible to compare segments based on different estimations. However, the values allow comparisons between groups within one segment. Take for example regionality. We see that all groups clearly prefer regional over non-regional production. Looking at the supplier type, we see that those knowing about biomethane favor energy corporations, while those not knowing about it favor municipal utilities. Looking at the gas mix, we clearly see that all groups clearly favor biomethane products with shares

**Table 5**
Mean utility values from the HB model for consumer segments. *An interpretation of the prohibitions of feedstock (n.n.) would not have made any sense here. We therefore re-centered the three meaningful values around zero. The sum of values therefore does not equal zero.

| | | Knowledge biomethane | | Renewable electricity at home | |
|---|---|---|---|---|---|
| | | Unknown | Known | No purchase | Purchase |
| | n: | 289 | 223 | 295 | 217 |
| **Attribute** | **Attribute levels** | | | | |
| **Gas Mix** | BM: 5% | 24.0 | 22.8 | 28.8 | 16.2 |
| | BM: 10% | 33.0 | 38.6 | 35.7 | 35.1 |
| | BM: 50% | 9.2 | 30.0 | 13.9 | 24.2 |
| | BM: 100% | −16.7 | 8.8 | −12.4 | 3.8 |
| | SNG: 5% | 38.6 | 36.3 | 40.8 | 33.4 |
| | SNG: 10% | 26.8 | 16.6 | 24.1 | 20.0 |
| | SNG: 50% | −9.3 | −13.2 | −10.6 | −11.6 |
| | SNG: 100% | −34.8 | −51.8 | −39.1 | −46.4 |
| | BM: 50%, SNG: 50% | −70.8 | −88.2 | −81.2 | −74.6 |
| **Labels** | No label | −13.0 | −18.6 | −14.0 | −17.4 |
| | TUEV | −11.0 | −2.1 | −7.7 | −6.3 |
| | GGL | −8.3 | −11.7 | −7.9 | −12.3 |
| | Fake | 2.7 | 1.9 | 1.8 | 3.1 |
| | TUEV + GGL | −3.0 | −5.9 | −4.3 | −4.2 |
| | TUEV + Fake | 9.2 | 16.3 | 12.9 | 11.6 |
| | GGL + Fake | 7.4 | 5.4 | 4.9 | 8.7 |
| | TUEV + GGL + Fake | 15.8 | 14.6 | 14.2 | 16.8 |
| **Regionality** | Not Regional | −7.7 | −3.3 | −6.0 | −5.4 |
| | Regional | 7.7 | 3.3 | 6.0 | 5.4 |
| **Biomethane Feedstock*** | Energy crops | 1.4 | 4.0 | 2.6 | 0.7 |
| | Waste | −1.7 | −4.0 | −2.6 | −4.3 |
| | Mix | 1.7 | 3.4 | −0.1 | 4.3 |
| **Supplier Type** | Energy corporation | −2.0 | 2.4 | 0.1 | −0.2 |
| | Municipal utility | 2.5 | −2.1 | 0.6 | 0.3 |
| | Cooperative | 0.5 | −0.3 | −0.7 | −0.1 |
| **Yearly Price** | Level 1 | 124.6 | 63.8 | 105.2 | 88.6 |
| | Level 2 | 26.4 | 20.9 | 23.9 | 24.0 |
| | Level 3 | −10.0 | −0.4 | −6.6 | −4.8 |
| | Level 4 | −30.0 | −10.9 | −22.9 | −20.0 |
| | Level 5 | −48.2 | −28.4 | −42.1 | −36.1 |
| | Level 6 | −62.8 | −44.9 | −57.5 | −51.6 |

up to 50% and SNG products up to 10% shares. Only those knowing about biomethane and those purchasing renewable electricity have a higher preference for the 100% biomethane product.

Looking at the yearly price, we again see quite comparable results between segments and groups: Low(er) prices are generally favored. However, the ranges (differences between values of first and sixth level within each group) are much higher between those knowledgeable about biomethane and those who are not, as well as between those sourcing renewable electricity and those who are not.

This insight from the attribute level perspective is also reflected in the attribute importance scores of the different groups, displayed in Table 6. We can see here that the yearly price is less important to those knowledgeable about biomethane than to those who are not. A correspondingly higher level of importance is assigned to the gas mix, labels and feedstock. These results also hold true for those purchasing renewable electricity; however, the difference is less pronounced.

## 4. Discussion

We found knowledge gaps regarding the two technologies, which were much more pronounced for SNG compared to biomethane. To ensure validity of the DCE, an explanatory video was added to the survey which has surely reduced these gaps. When interpreting and discussing our results, this should be considered.

**Table 6**
Attribute importance scores of consumer segments.

| Attribute | Knowledge biomethane | | Renewable electricity at home | |
|---|---|---|---|---|
| | Unknown | Known | No purchase | Purchase |
| **Gas Mix** | 31.1% | 36.5% | 32.9% | 34.2% |
| **Labels** | 14.6% | 18.0% | 15.6% | 16.9% |
| **Regionality** | 4.9% | 5.3% | 5.1% | 5.1% |
| **Biomethane Feedstock** | 12.3% | 15.1% | 13.2% | 13.9% |
| **Supplier Type** | 5.9% | 6.9% | 6.1% | 6.6% |
| **Yearly Price** | 31.2% | 18.1% | 27.1% | 23.4% |

We found the gas mix to be most important to consumers, which comes as no surprise since it is the core attribute of a renewable gas product. Looking at the importance scores, however, it was surprising to see that biomethane products in general are clearly preferred over SNG products. Given the high profile of the fuel-versus-food debate around energy crops and the central role of biomethane in this debate (Herbes et al., 2014), we had expected SNG to be more popular with consumers than biomethane. That it was not, together with the results on feedstock preferences that we discuss below, seems to indicate that the negative perception of energy crops and biogas has improved. This is also supported by a survey published in 2022 in which 39% of respondents said that they are in favor of an expansion of energy-crop-based bioenergy production (Agentur für Erneuerbare Energien, 2022). Negative utility values for higher shares of renewable gases most certainly stem from higher prices: As shown in Table A3 higher shares came with higher prices, therefore reflecting the real market situation. In turn, this potentially discouraged participants to opt for the higher shares.

It was also not surprising to find price ranking second in terms of attribute importance to consumer decisions about a gas tariff. However, the small gap to the attributes in third and fourth position was unexpected and provides an encouraging message for gas providers, as they can, at least partially, influence those product attributes.

The third most important factor influencing respondent choices was labelling used in the choice sets. The results here offer surprising insight into consumer thinking. Respondents show a clear preference for labeling, with “No label” consistently least preferred. Also Bengart and Vogt (2023) showed that labels increased the propensity of consumers to buy environmentally friendly energy. But we could not have anticipated the labeling configurations that solicited higher preference scores. The fake label included in the choice sets not only outscored the two established environmental labels, TUEV and GGL, but boosted the utility of any combination it was in. When only one label was in the choice, respondents ranked GGL, the strictest label assuring the highest environmental benefit, last among the three labels. Our fake label ranked first. In label combinations, the two established labels used together scored slightly better than either alone, but the strongest preferences were shown for combinations that included the fake label. Whether used with GGL or TUEV, the fake label combined with the established label scored higher than the two established labels in combination. Combining all three labels revealed a “more, the merrier” effect, as this choice configuration scored the highest of all options.

These results hold even after segmenting respondents into consumers with and without knowledge of biomethane, or into those with and without a renewable electricity tariff. To a certain a degree, this segmentation relativizes knowledge and experience as decision drivers. Yet we found those knowledgeable about biomethane, and those currently buying a renewable electricity tariff still chose the fake label over the two established environmental labels, and still preferred any combination with the fake label over one without.

These results point clearly to confusion among consumers and provide further evidence for their lack of knowledge about the renewable energy market (Li and van 't Veld, 2015). Eleven years after Mattes (2012) found that few consumers in Germany understand labels in the electricity market, we can say the same for the gas market. Although the labeling companies, TUEV or GSL (GGL), have not changed, their labels apparently have not established a clear identity in the consumer mind.

Ranking fourth in importance as a tariff attribute is biomethane feedstock, with three choice levels -energy crops, waste, or a mix of the two-presented. Respondent choices led to surprising outcomes. Notably, energy crops were favored over waste. This is in stark contrast to existing literature where waste-based biogas has always been found to be preferred by consumers (Forsa, 2012; Schumacher and Schultmann, 2017). The preference for energy crops over waste was even more pronounced among respondents having biomethane knowledge.

This result was puzzling, and so we cross-checked it with results from other questions asked in the questionnaire accompanying our choice experiment. Those results corroborated the preference choices: 48.8% of the respondents agreed with the statement "I do not see the use of energy crops as critical"; 33.6% were neutral and only 17.6% disagreed. Further, 64.1% agreed with "I find the production of biogas sustainable" and only 10.9% disagreed.

The results of the choice experiment in combination with these answers indicate a drastic change in public opinion of biogas, which for many years has been negative. The most likely reason for the change is that the public debate over biogas has subsided from the fierce levels it reached in 2011 and 2012 (Herbes et al., 2014). This in turn is probably the consequence of the fact that the biogas industry underwent a period of dynamic growth in Germany, peaking with the construction of 1526 new plants in 2011, after which the number of new plants plummeted to levels between 100 and 200 per year from 2014 (Biogas Fachverband, 2022).

Our results on regionality and supplier type showed that these attributes, though often mentioned in past studies, are of relatively minor importance to renewable gas customers, regardless of their knowledge of biomethane or their current use of renewable electricity.

## 5. Conclusion and policy implications

We conducted a choice experiment with 512 households in Germany to identify consumer preferences for renewable gas tariffs. Our study is the first to demonstrate the relative importance of different product attributes to consumer decision makers. Our research questions and the answers we found follow.

1) Which product attributes are important to consumers in the renewable gas for heating market and how important are these attributes? The gas mix was clearly the most important attribute (importance score: 33.5%), closely followed by the price (22.5%). Labels came in third (16.1%) and biomethane feedstock fourth (13.5%). Supplier type (6.3%) and geographical origin, i.e. regionality (5.1%) were of minor importance to our respondents.
(2) How do preferences vary by different consumer groups? We segmented consumers based on whether they had knowledge of biomethane and whether they used renewable electricity. In terms of attribute importance, there were no large differences in either segmentation, but those having knowledge of biomethane and those with a renewable electricity tariff did assign less importance to price than the complementary segments. This points to these consumers as potentially valuable future customers.

With regard to the gas mix, consumers with biomethane knowledge and those who have a renewable electricity tariff prefer products with a higher biomethane share. However, this does not hold true for a SNG share. Regarding labels and regional production, we did not find any major differences in preferences between those with and without biomethane knowledge or those currently using or not using renewable electricity. All consumers preferred regional production. All consumers derived higher utility from GGL or TUEV with the fake label than from either used alone or together, and all consumers derived the highest utility from the three labels used together.

Biomethane knowledge had no influence on the preferences for biogas substrate. However, renewable electricity customers preferred a mix of energy crops and waste while non-customers preferred energy crops. Regarding the supplier type, buying renewable electricity did not make a difference, but those with biomethane knowledge preferred commercial providers while those with no knowledge preferred municipal utilities. In line with the lower importance of the price, those with biomethane knowledge and those with a renewable electricity tariff show less aversion towards higher price levels.

To summarize, our results indicate that biomethane knowledge and buying a renewable electricity tariff are linked to a higher WTP for renewable gas products and preferences for gas products with a higher renewable content. For all other attributes, the links between attribute importance and preferences on the one hand and knowledge and renewable electricity on the other hand were non-existing or weak.

### 5.1. Implications for energy companies

Gas providers can take away a number of learnings from this study to improve their marketing strategies, especially against the background of selling a low-involvement product in a market with behavioral lock-in regarding energy choices of consumers (Rilling and Herbes, 2022; Bai et al., 2023). First of all, the importance of price is significantly lower for consumers who know about biomethane and a little lower for those who source a renewable electricity tariff compared to other consumers. This hints at opportunities for cross-selling, since most providers offer both electricity and gas tariffs, and existing electricity customers could be a promising target group, especially renewable electricity customers who are significantly more knowledgeable about biomethane than customers with no renewable tariff. Not surprisingly, companies will find these target customers predominantly among those with a university education.

The selection of biomethane feedstock cannot be based solely on consumer preferences: For one, the preferred energy-crop-based gas is cheaper to source anyway and second, many providers partly rely on short-term contracts and so will face difficulties making reliable statements on their feedstock when acquiring long-term customers.

Regarding product policy, the utility scores of the different gas mixes point to opportunities that lie in offering tariffs with a low percentage of biomethane and SNG. This also makes sense, since the cost to providers of biomethane is double that of natural gas, at least before the current turbulences in the gas market, and so the gas mix is by far the biggest cost driver for providers. Keeping the percentages low thus helps in keeping end customer prices at a reasonable level.

Educating consumers about the meaning of the labels is certainly necessary, especially for those companies which fulfill the strict demands of the GGL standard. Redesigning labels to make them more attractive and memorable could be another approach. Investing in multiple labels may also seem a promising strategy from the individual perspective of gas companies, although we of course do not recommend inventing a fake label or confusing consumers with irrelevant information.

But labeling can be more cost effective than manipulating the gas mix design. The gas mix is a strong cost driver, so providers need to check the WTP that is incurred by different levels of biomethane and SNG. Labels, on the other hand, are not very costly. According to one provider that we contacted after the survey, a label can cost less than 0.05 EuroCt/kWh for a product that sells 25 GWh per year and more.

Labeling questions touch on communication with the consumer, which seems to be a daunting task for providers marketing SNG products. Consumers are utterly unfamiliar with the technology and thus are cautious in selecting it despite its environmental benefits. But the study of Rilling and Herbes (2022) already indicates the fact that surplus renewable electricity is used to produce SNG resonates well with consumers. Here is a concrete benefit that can be communicated to consumers.

For providers of demanding eco-labels like GGL, our study reveals an even greater communication task. Our results demonstrate that even those knowledgeable about biomethane or who source renewable electricity are unable to recognize the superior eco-benefits that a demanding label guarantees. This is probably disappointing for labelling organizations which have been in the market for more than 20 years (GSL) or nearly ten (GGL) (G.S.L, 2022). Apparently, the market with its free interplay of consumers, providers and labeling organizations with different requirement levels has not functioned well even after a long time.

### 5.2. Implications for policy makers

This opens up a role for policy makers. First, a standardized state-run labeling scheme with a gradation of eco-requirements could support more informed consumer choices. There have been frequent demands by researchers for label standardization (Li and van 't Veld, 2015; Draper et al., 2013), possibly administered by the federal government (Rommel et al., 2016). However, policy makers should consider challenges like transaction costs, need for coordination and the duration when establishing this kind of label.

The second role for the state lies in raising consumer awareness of and knowledge about renewable gas alternatives in general and making sure that consumers get the information they need to make informed choices. As Herbes et al. (2021) have shown, providers often do not provide information on product attributes that are important to consumers. This leaves consumers, even those who know what they want, in the dark about selecting a product that meets their preferences. Thus, mandating that providers disclose all relevant information would help influence consumer demand for renewable gas.

And finally, policy makers can consider the option of a compulsory biomethane or SNG quota for gas providers or households to largely replace market mechanisms. The fundamental decision to establish a compulsory quota depends on how policy makers view two questions: should the heating sector be prioritized for biomethane over electricity production and how urgent do politicians deem decarbonization of the heating sector?

The questions are intertwined. As Herbes et al. (2021) have summarized, carbon savings from using biomethane are higher in electricity and transport than in heating. However, given the long renovation cycles of heating systems and the alternatives for greening electricity and transportation, renewable gases seem the only option for a quick decarbonization of the heating sector. Due to the war in Ukraine and the reduced gas flow from Russia, politicians have also begun to consider the supply security aspect of different gas sourcing strategies. There is a clear political will to become more independent of Russia, so using renewable gases for heating has moved up the political agenda.

But let us put things in perspective. Even if all the biogas plants in Germany were to upgrade their gas to biomethane immediately and channel the biomethane into the heating and cooling sector, the resulting biomethane supply would cover a mere 4% of the private gas demand in Germany (own calculations based on Bundesnetzagentur and Bundeskartellamt (2022) and Arbeitsgemeinschaft Energiebilanzen (2020).

Moreover, equipping biogas plants that use their biogas to generate electricity on-site with an upgrading facility is not realistic in many cases. First, biogas plants often sell the heat to third parties, meaning they are bound by existing contracts (Herbes et al., 2018b). And second, many plants are too small to make gas upgrading economically viable. Replacing the gas demand in heating and cooling by SNG from PtG plants would require tens of thousands of new large wind turbines which, however, could also be used in a more direct way (e.g. heat pumps) or stored in large-scale batteries, therefore reducing the availability of necessary surplus electricity. These numbers show that both biomethane and SNG can play a role in decarbonizing the heating sector, but they should be seen as elements in a larger portfolio of solutions.

### 5.3. Limitations and avenues for further research

One limitation of our work lies in the fact that our choice experiment was run before the war in Ukraine started. It is likely that consumer preferences have been affected, e.g. regarding the preferences for regional or national origin. Moreover, price levels have changed and the relative price competitiveness of biomethane has increased. This argument has already been put forward by the European Biogas Association (2022) before the Russian invasion in Ukraine, which has only amplified this effect (Abdalla et al., 2022).

Second, surveys about a low-involvement product like gas for heating already hampers informed decision-making. Doing so for a new and unknown product like SNG reinforces this even more, which was an obstacle in our analysis. In this regard, also social desirability should be mentioned: With renewable gases our study focus is on products, that consumers might opt for because of perceived social norms. However, we consider this to be less problematic in an anonymized online questionnaire setting.

Third, we employed a choice experiment. While choice experiments are widely used both by researchers and marketing practitioners, they can only simulate a purchasing decision and therefore come with some limitations: Our study focused one market (Germany) using pre-identified product attributes. This selection might not be sufficient to represent consumer diversity and might also differ between national markets. Furthermore, in our survey products were presented decomposed using a combination of descriptions and visualizations (e.g. labels and gas shares). This presentation differs from, say, provider homepages, their leaflets or price comparison portals (Tabi et al., 2014; Yilmaz et al., 2021).

Fourth, we also need to point to some issues regarding our sample. We used a panel providing access to a representative sample. To survey only those informative for our research scope, we had to exclude people not using gas for household heating and/or people with no decision-making authority over their gas tariff. The comparably high share of male respondents suggests that decisions about a heating tariff are male-dominated. Furthermore, the comparably high share of households sourcing renewable electricity could potentially influence positively consumer evaluations of other renewable energy sources.

Fifth, while we explicitly focused on the demand side of renewable gases, we should briefly consider the supply side in this regard: Many analyses do not see a mid-to long-term perspective for SNG in the private heating market. However, upgrading biogas to biomethane could be an option for the short-to mid-term perspective -especially if the dominant business model (electricity generation) comes to an end and the identified potentials (i.e. 17-35 billion cubic meters) can be realized (Abdalla et al., 2022).

Still, our study can provide a launch pad for future research: First, the effect of the war in Ukraine and the ensuing high uncertainty of the gas supply in Europe are worth analysis. A longitudinal study that replicates our work and captures short- and long-term effects would be especially interesting. A longitudinal approach would also be promising to explore if and how a longer exposure to the PtG technology through the media might change consumer preferences of SNG. Further studies could also look at real market data (revealed preferences) and other (Non-)European countries.

Second, our study revealed a major change in the perception of using energy crops for biogas production. This now seems to be viewed positively. It would be intriguing to explore the subjective logics that brought about the changes. A qualitative interview study could look into how consumers see the change in their own perception of biogas and energy crops and what events or stories they link it to.

Third, the reasons for the fake label used in this study being that attractive remain unclear. Further research could look into label (graphic) design and how consumers react to this, e.g. building upon an eye-tracking study.

Fourth, a discourse analysis of the media coverage of biogas and energy crops, maybe building on the study by Herbes et al. (2014), could reveal changes in the contents and frequencies of different storylines and thus examine one potential driver for the positive perception of energy crops.

## CRediT authorship contribution statement

**Benedikt Rilling:** Conceptualization, Formal analysis, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Peter Kurz:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. **Carsten Herbes:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing.

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113857.

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