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Synthetic natural gas in the private heating sector in Germany: match or mismatch between production costs and consumer willingness to pay?

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Abstract

Background The residential heating sector in many European countries requires a fundamental transformation if it is to become climate neutral. Besides the introduction of efficiency measures and updating heating systems, scholars and practitioners consider replacing fossil fuels in existing heating systems a viable approach. Drop-in renewable gases such as biomethane and synthetic natural gas (SNG) cause considerably fewer carbon dioxide (CO_2) emissions than natural gas and can be used in natural gas boilers, the dominant heating system in many European countries. To move the ongoing debate around e-fuels forward, this study reports on a Discrete Choice Experiment with 512 respondents in Germany that analyzed consumer preferences and willingness to pay (WTP) for SNG. I build on these insights by comparing WTP to the production costs, making evidence-based decision-making possible.

Results The results show that consumers prefer renewable gases over natural gas. Comparing the two types of renewable gases, SNG and biomethane, reveals that consumers clearly favor the latter despite the criticism it has come under in the last 10–15 years. Consumers show a surprisingly high WTP for increasing shares of SNG, with premia of 40 to almost 70% over a natural gas-based tariff. Comparing production costs to the WTP reveals that only tariffs with small shares of SNG (5% and 10%) can be offered at cost-covering prices.

Conclusions Given the urgent need for a fundamental transition of the residential heating sector, marketers and policymakers should consider carefully whether it is worth channeling a rather unknown and expensive product like SNG into the voluntary market for heating gas, especially as biomethane is already established in the market and clearly a cheaper and more popular alternative.

Keywords Renewable gas, SNG, Willingness to pay, Consumer preferences, Discrete choice experiment, Residential heating

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Background

The residential heating sector faces the global challenge of reducing its climate impact while ensuring the comfort and well-being of millions of households without interruptions and at affordable prices [1]. This challenge is hugely complex: the residential sector in Europe accounted for 27% of the final energy consumption in 2021, with space and water heating accounting for almost 80% of that consumption. Heating in residential buildings still relies heavily on fossil fuels: approximately ¾ of the primary energy demand of the EU-27 comes from fossil fuels [2]. For home heating, the fuel of choice for decades in many European countries has been natural gas [3], including Germany, the country this paper focuses on. Accordingly, CO_2 emissions from residential heating have accounted and continue to account for a significant share of greenhouse gas emissions in the European Union (EU) [4].

Although some progress has been made in making Germany's residential heating sector less CO_2-intensive, it has missed its emission reduction targets for three straight years (2020–2022) [5, 6]. According to the latest analyses [7, 8], the sector is expected to miss the important 2030 interim target towards climate neutrality in 2045. So it comes as no surprise that the political discourse in Germany in 2023 has been dominated by disagreement over which legislative actions should be included in the Building Energy Act ('Gebäudeenergiegesetz'). These range from banning certain fossil-based heating technologies, to advocating for technological openness, to transition within existing infrastructure [9].

Households and consumers today have essentially three means of lowering the CO_2 they emit from heating their homes. The first is to take efficiency measures like retrofitting buildings with insulation or new windows. The second is to install new heating systems that are more efficient or based on alternative fuels, such as solar power or biomass. The third is to switch existing heating systems to more climate-friendly fuels like biomethane. Each approach has been investigated in the literature on consumer decision-making, but to varying extents. Taking efficiency measures (see, e.g., [10–12]) and the installation of new heating systems (see, e.g., [13–15]) have been the subject of many consumer studies. In contrast, switching to less CO_2-intensive fuels has received less academic attention, even though low renovation rates and long-life gas boilers make this approach highly relevant [16]. This paper, therefore, adds to the literature on switching to more climate-friendly fuels in existing heating systems.

Currently, there are three renewable gas technologies that could be used for the production of direct substitutes for natural gas: substitute natural gas from biomass (Bio-SNG), biomethane, and synthetic natural gas (SNG), which builds upon the power-to-gas (PtG) technology. Bio-SNG uses lignocellulose (e.g., wood or straw) as a feedstock to produce syngas, which is then purified, subjected to methanation, and further upgraded and purified. However, it has not yet advanced beyond early commercial or demonstration-only projects [17].

Against this backdrop, this paper analyzes the other two renewable gas alternatives, biomethane and SNG, in more detail. Biomethane is considered the most mature renewable gas: It harnesses the anaerobic digestion of biomass (e.g., energy crops, manure, or other waste) to produce biogas. This biogas can be used directly to produce electricity and/or heat, which is the most common form of use [17]. In Germany, for example, there were 9.876 biogas plants with an installed electric capacity of 5.895 MW in 2022 [18]. The biogas produced can be purified into biomethane, which is a direct substitute for natural gas and can be used in the existing infrastructure [19]. In Germany, 242 biogas plants with biomethane injection were in operation in 2022 [18].

Like biomethane, SNG is chemically identical to natural gas. It does not need to be imported and leads to significantly reduced CO_2 emissions compared to natural gas. In comparison to biomethane, which has been studied extensively (e.g., in [20–23]), SNG technique is a newer and less established technology. It builds upon PtG technology, using surplus electricity from renewable sources, such as solar power or wind to generate hydrogen. Just like Bio-SNG, it has not reached market viability yet. However, this is expected to change, as researchers consider PtG technology and hydrogen-based solutions as crucial for energy systems relying on 100% renewables [17, 24]. The generated hydrogen can be upgraded to SNG using CO_2 (e.g., from a biogas upgrading plant) in a methanation plant. With increasing shares of fluctuating renewable energies in the electricity mix, PtG and SNG act as an interim storage system and can therefore be regarded as additional medium-term solutions for replacing natural gas in multiple sectors, where one of which could be residential heating [19, 25, 26]. Currently, SNG incurs higher production costs than biomethane; however, these are expected to come down. The focus of this paper is therefore on the most important current substitute (i.e., biomethane) and one of the most promising additional future substitute (i.e., SNG) for natural gas in residential heating and beyond.

Renewable gases for residential heating have previously been studied from a consumer perspective: a qualitative study from Germany that built upon interviews with consumers as well as upon interviews and focus groups with industry experts [16] found gas tariffs for residential heating to be a low-involvement product. The authors analyzed two renewable gases for existing heating systems: biomethane and SNG. Consumers were unfamiliar with SNG and neutral about it; the storage potential was however rated positively. Biomethane was better known but received mixed evaluations: consumers saw its environmental benefits as positive but the usage of energy crops and large-scale production as negative. A discrete choice experiment (DCE) study from Germany [27] found knowledge gaps for both technologies. Biomethane was preferred over SNG despite the 'food vs. fuel' debate, which is tightly connected to bio-based energy carriers [28]. Kim et al. reported that South Korean households would accept a 5% price premium for renewable heat over fossil heat [29] regardless of the renewable source. Another study from South Korea revealed a 32% willingness to pay (WTP) for renewable heat based on biomethane [30]. They suggest this as a starting point for further research that compares WTP to production costs, emphasizing that renewable heating is costlier than natural gas. This also leads Bai et al. to conclude that affordability is key for clean(er) heating and requires further investigation [31]. While this last conclusion holds true in other national settings, the aforementioned studies from South Korea cannot be transferred one-to-one to a European/German setting. However, given similarities such as high shares of natural gas in primary energy consumption, high import dependency, and a long-lived and slowly replaced natural gas infrastructure [32], these studies can still inform and guide the analyses in this paper. Given the lack of existing research focussing on WTP for renewable heating fuels in Europe and in view of the controversial debate on hydrogen and synthetic fuels for residential heating, sparked by the enactment of the Building Energy Act in Germany in 2023 [9], this paper aims to provide new insights into consumer preferences and WTP. If the potential of the innovative SNG technology to reduce CO_2 emissions in residential heating systems is to be realized in a voluntary market, the production and consumer sides need to come together. Consumer WTP needs to meet real production costs if change is to happen, especially at a basic level like heating a home. Hence, this study raises the following two research questions (RQ):

> *RQ1: How much are consumers willing to pay for different shares of SNG in their residential heating gas tariff?*
> *RQ2: How does the cost of producing SNG compare with consumer WTP in the residential heating market?*

The goal of this paper is therefore twofold: First, to provide insights into consumer preferences and WTP for renewable gases in the heating market, with a dedicated focus on SNG—an aspect currently lacking in the literature. Second, by combining WTP and production costs it bridges the gap between the demand and supply sides—an aspect called for in the literature [30] but not yet realized empirically.

Methods

Answering both research questions requires sound data from two perspectives: the demand side and the supply side. I was able to derive SNG production costs from the literature, whereas data on consumer preferences and WTP for SNG had to be collected via a DCE.

Consumer preferences and WTP for SNG

There are two distinct approaches to measuring consumer preferences for goods, services, or even policies. One measures revealed the other stated preferences [33]. Approaches built on revealed preferences come with the great disadvantage that only existing products or services can be examined ex-post (e.g., through market data). Measuring stated preferences allows for "…investigating both goods which are available on the market and also hypothetical products" [34]. Given the relative novelty of SNG, this study used a stated preference approach. I developed the DCE to identify those preferences as well as the WTP values [33].

When DCEs were first introduced, it was only possible to evaluate these experiments on an aggregate level [35], but the development of Hierarchical Bayes (HB) estimation techniques has opened new and more sophisticated possibilities. Using HB allows a researcher to calculate part-worth utilities on a pseudo-individual level [36–38], even if there is little data for each respondent [39].

Developing a DCE and applying it to a specific case require breaking down the good or service at hand into product attributes (e.g., shares of SNG) with different levels (e.g., 5%, 10%, 20%). The underlying idea rests on the assumption that consumers demand features or characteristics (i.e., attributes) of products and services rather than products themselves [40]. Products and services can therefore be described as bundles of attributes that generate varying utilities for consumers [41]. Ultimately, consumers strive for maximum utility when making their decision for or against a product [42, 43]. This ties in with the well-established random utility theory. Its basic axiom can be described as [44–46]:

$$U_{\text{in}} = V_{\text{in}} + e_{\text{in}}$$

where U_{in} being the latent, unobservable utility that individual n associates with alternative *i*. This utility is the sum of V_{in}, the systematic and explainable utility component, and ε_{in}, the random and unexplainable component [44].

Measuring the corresponding (part-worth) utilities of different attributes (e.g., SNG share) requires products that vary in attribute levels, such as different percentages of SNG in the product. Accordingly, products are generated from an independent but systematic combination of different attribute levels. In the actual survey, the respondents are confronted several times with these different products and have to decide in favor of one configuration (i.e., a discrete choice). These so-called choice tasks are repeated multiple times to acquire enough data on an individual level to calculate pseudo-individual part-worth utilities. These in turn allow researchers to make sound assertions about preferences.

The DCE conducted in this study to identify preferences and WTP for SNG uses a multistep procedure:

Experimental design

Realistic and efficient choice sets are the key to a DCE [34, 47, 48]. The importance of "…designing surveys, so that they represent real choice situations as closely as possible" [34] underscores the need for well-selected attributes and attribute levels. To this end, this study employed a broad literature analysis combined with 22 exploratory interviews with heating customers [16]. It yielded the attributes and levels shown in Table 1.

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 increase levels (from 0 to 904%), see Table 3

*Only applies to biomethane products and was not shown with SNG products in the DCE

Table 2 Product combinations (varying shares of different gas sources) used in this study

Product	Natural gas share	Biomethane share	SNG share
Reference Product	100%	0%	0%
BM: 5%	95%	5%	0%
BM: 10%	90%	10%	0%
BM: 50%	50%	50%	0%
BM: 100%	0%	100%	0%
SNG: 5%	95%	0%	5%
SNG: 10%	90%	0%	10%
SNG: 50%	50%	0%	50%
SNG: 100%	0%	0%	100%
BM: 50%, SNG: 50%	0%	50%	50%

Following [49], the Gas Mix attribute covered only renewable shares actually available on the biomethane heating market. These were transferred to SNG products. Table 2 lists the different combinations.

To ease reading, products will be referred to by their renewable share: i.e., SNG: 10% stands for an SNG share of 10% and a natural gas share of 90%; BM denotes biomethane.

Energy studies have followed two approaches to operationalize prices for WTP investigations. The first uses a per unit price (i.e., per kWh or per m^3) as in [30, 50–52], and the second uses aggregate and general absolute numbers like monthly or yearly costs [34, 53–55]. While both approaches are easy to realize and facilitate direct comparison between responses, they suffer from three problems. First, only a small share of consumers knows the markets well enough to know about general per unit prices or even their specific tariffs. Second, a consumer's usual payment is not per unit but based on an estimated monthly installment that includes other price components, such as taxes, grid fees, and CO_2 prices. This is then settled in a yearly bill that takes actual consumption into account. Third, the total heating costs depend very much on housing parameters like living space, refurbishment status, and construction year of the building. None of these are captured by the conventional approaches.

To get as close as possible to the individual heating cost realities of respondents, I calculated an individual yearly price for each respondent. My approach followed three steps. First, a series of questions regarding the housing parameters were included in the survey (i.e., construction year of building, refurbishment status, living space). Using this information in the second step, the average final energy demand (kWh) per annum of the dwelling unit was calculated using data from the TABULA building typology [56]. Third, using the average gas price (€/kWh) for private households, differentiated according to the different housing types from [57], the yearly price of the reference product (100% natural gas) was calculated for each respondent.

This approach has the advantage of being based on housing parameters relevant for heating and uses a uniform calculation method that avoids ambiguities when, for example, asking about yearly costs. It thereby assigns the survey participants a realistic cost estimate close to their actual payment.

For each share of renewable gas, I used six individual levels of price increases, as shown in Table 3.

The lowest level (= no increase) was used for all products. Although this might seem unrealistic given current market prices, this level was included to cover unreserved aversion toward a renewable gas product (opting against it although there is no price increase). The upper limits had to be chosen at a level that would include all accepted price premia in order to avoid under-coverage (as, e.g., in [39]). For biomethane, market prices from [49] were used and varied; for SNG, the calculated production costs came from [58]. Instead of using identical price levels between products, the increases within one product were chosen as uniformly as possible while taking into account the aforementioned price data as well as lower and upper limits.

Data collection and analysis

The final experiment, as well as the data collection and its analysis, was designed and carried out in close cooperation with a market research institute (*bms marketing research & strategy*). Cooperating with *bms* opened access to the *Kantar Profile Network*, a panel with over 3,700,000 panelists worldwide, including a representative sample from Germany. To determine eligibility for the online survey, participants were screened against three criteria: They had to be at least 18 years old, use natural gas for residential heating, and have decision-making power over the gas provider and tariff. Following ten pre-tests, the questionnaire was adjusted to reach a final completion time of 17 min. This period included a mandatory explanatory video lasting approximately 5 min (see https://youtu.be/dOd77MaW4xI). It was produced due to previously identified knowledge gaps regarding renewable gases, especially SNG.

Following the soft launch of the survey at the end of May 2021, 55 responses were checked for data quality, duration, and completeness. The main survey then ended on June 10, 2021 with 523 responses after straight liners and (too) speedy respondents were excluded. After a quality check, another 11 cases had to be removed from further analysis due to random answer behavior which would have impaired the estimation of part-worth utilities by creating more noise in the data. Eliminating cases after a quality check is common when conducting DCEs, as it improves the quality of the HB estimation model [39, 59]. Each respondent had to complete eleven choice sets (see Fig. 1) which each contained four product alternatives plus the reference product (100% natural gas). This yielded a total of 5632 active choices for estimating part-worth utilities and WTP. *Sawtooth* software was used to conduct field work and analyze the DCE data.

Following the procedure described in [39] and [27], a HB regression was applied to estimate pseudo-individual part-worth utilities as well as WTP. It is based on a multi-method approach using a two-level model: A multinominal logit model is used to analyze the choice of one option over another for each respondent, i.e., the lower level, while the upper level assumes that the part-worth utilities follow a multivariate normal distribution at the population level. Because it captures preference heterogeneity very well, this approach is regarded as state-of-the-art for measuring consumer preferences using DCEs [60]. Regression statistics pointed to a reasonably good model fit [61, 62], with a Pseudo R-Squared of 0.62 and an average Root Likelihood value of 0.54, which is 2.75 times greater than the null likelihood value of 0.2 (1/5)

Table 3 Price levels used in the DCE for each product

BM: 5%	BM: 10%	BM: 50%	BM: 100%	SNG: 5%	SNG: 10%	SNG: 50%	SNG: 100%	BM: 50%, SNG: 50%
0%	0%	0%	0%	0%	0%	0%	0%	0%
5%	5%	25%	50%	10%	10%	50%	100%	50%
10%	13%	54%	104%	15%	20%	150%	300%	100%
15%	30%	100%	150%	20%	40%	200%	400%	156%
20%	40%	150%	200%	26%	52%	259%	517%	200%
25%	50%	200%	250%	45%	90%	452%	904%	253%

for completely randomized choices between the five options in every choice set.

Calculating consumer WTP for SNG

To estimate consumer WTP, the derived part-worth utilities are transformed by estimating price sensitivities/price-response functions. WTP is then given as maximum price that consumers are willing to accept for a product feature [39, 63, 64]. Here, one advantage of DCEs comes into play: By integrating a “No Choice” or “Reference Product” option, which for this study was a 100% natural gas tariff, the utility value of the status quo can be used as a reference. WTP values for other attributes can then be calculated against this reference.

Although the choice tasks in the DCE used absolute yearly prices, the DCE was based on relative price increases (see Table 3). This means the results show the WTP values that are relative to the reference product. In order to match absolute production costs to the relative WTP, the latter needs to be converted into absolute figures. To do so, the additional WTP values were multiplied by the end consumer price for the reference product. For the *best case-scenario* (see next chapter), this was 7.06 €ct/kWh, which is the average 2021 end consumer price including all price components [65]. For the *normal case,* the January 2021 price of 12.21 €ct/kWh was used, which takes into account increased procurement costs but not the highly elevated costs following the Russian invasion of Ukraine [65].

SNG production costs

Unlike the WTP for SNG, its production costs, i.e., the supply side perspective, have been studied in the literature. Böhm et al. [66] used a modelling approach to estimate 2020 costs, which came out between 0.30 and 0.80 €/kWh_{SNG} in the short- to mid-term. These costs could,

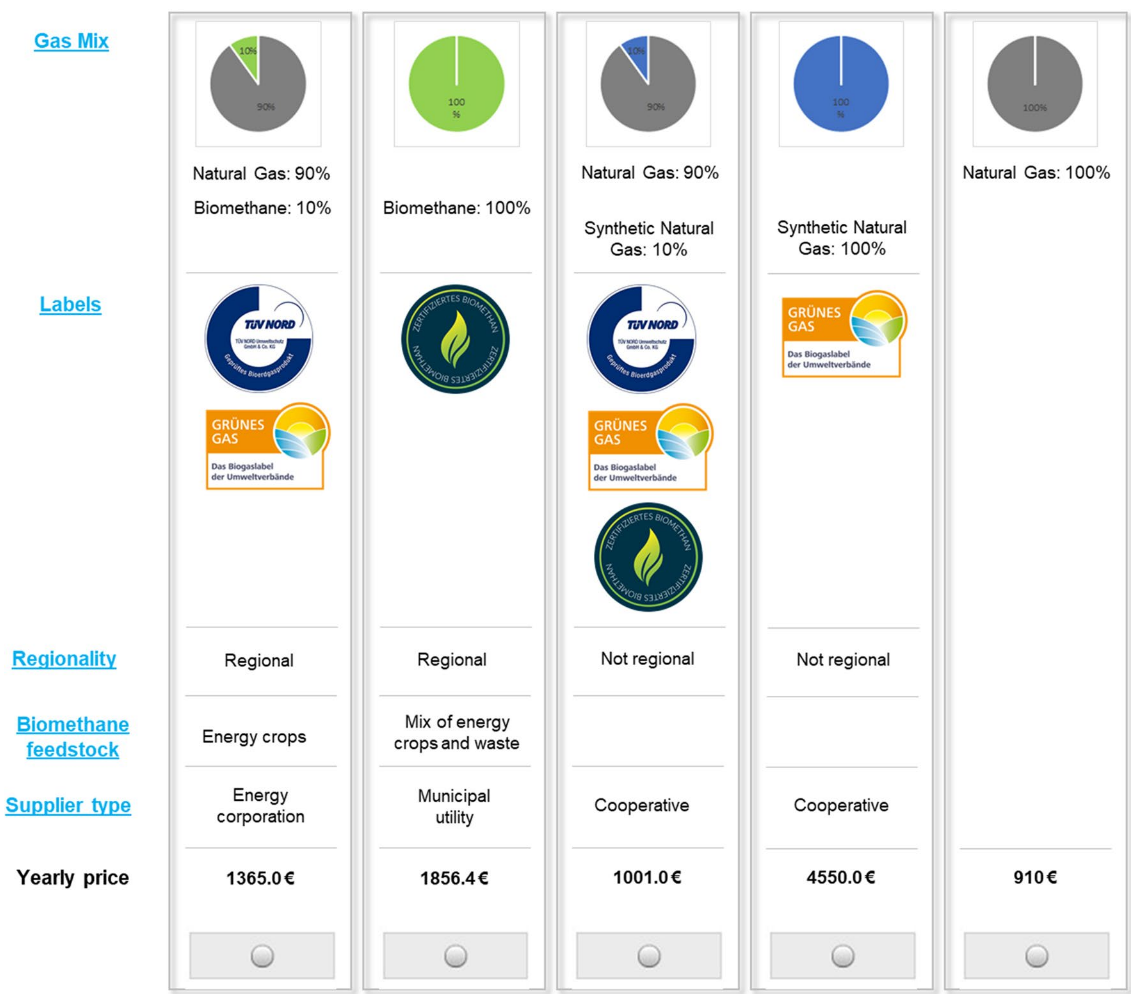

Fig. 1 Exemplary choice set

according to the researchers, go down to 0.15 €/kWh_{SNG} and even lower in the long-term, especially when using large scale PtG plants and given the likelihood of significant cost reductions in the renewable electricity supply. In their scenario analysis from 2021, Devaraj et al. [67] found short-term costs between 0.432 and 1.959 €/kWh_{SNG}, which they expected to decrease to 0.14–0.62 €/kWh_{SNG} over a period of 20 years depending on demand and the operational hours of methanation plants and electrolyzers. In their techno-economic assessment of 2022, Vega Puga et al. [26] found costs of 0.33 to 4.22 €/kWh_{SNG}, with electrolyzer type, electricity price, and operational hours being the most influential scenario parameters.

For multiple reasons, this study relies upon SNG production costs taken from [58], which was published in 2022 as part of a research project funded by the German Federal Ministry of Economics and Energy (grant number 03EI5401C) focusing on the integration of PtG and biogas/biomethane plants to produce renewable gases. For one, it is the most recent publication calculating SNG costs in the German market. Second, it considers the latest developments in the energy markets following the Russian invasion of Ukraine. Third, the analyses conducted go beyond mere production prices and consider consumer end prices in the heating market by taking into account further price components, such as taxes or other levies. Table 4 provides an overview of the different scenarios used and the derived SNG production costs (i.e., SNG alternatives). The two SNG alternatives were selected based upon the criteria of efficiency and representativeness. As the size/performance of biogas and biomethane plants have a strong impact on SNG production, two alternatives were selected that reflect the price range accordingly. However, it should be mentioned that the selected plant sizes do not perfectly reflect the situation in Germany, which is characterized by many and rather small plants.

For both scenarios, investment costs (e.g., the construction of electrolyzers and methanation plants) as well as operational costs were considered. For the latter especially, electricity prices are highly relevant. The two scenarios therefore differentiate between two price scenarios: The *best-case* assumes the wholesale price of 0.05 €/kWh, which corresponds to the German spot market price before the COVID-19 pandemic; the *normal-case* assumes an electricity price of 0.10 €/kWh, which takes into account the developments of the spot market price following the Russian invasion of Ukraine and also considers price decreases that followed short-term increases. For a detailed description, please see [58], p. 92ff.

The derived SNG production costs are consistent with the aforementioned studies. Despite different approaches to modelling, system boundaries, and system components, all researchers identify two main cost drivers of SNG production: electricity costs and the operating hours of the electrolyzer and the methanation plant. The range of these drivers is reflected in the selected scenarios and alternatives. Researchers also agree future cost reductions can be expected from efficiency gains and developments in this rapidly evolving technology. Still, even in optimistic scenarios, SNG costs are significantly higher than current prices for natural gas.

The researchers in [58] take the estimated costs one step further by adding additional price components that consumers in the heating market have to pay (based upon [65]):

- Sales costs: 0.4 €ct/kWh
- Grid fee incl. metering and metering point operation: 1.64 €ct/kWh

Table 4 Different scenario combinations and derived SNG production costs for two alternatives from [58]

	SNG alternative 1[a]	SNG alternative 2[b]
	Combination of a biogas upgrading plant using a membrane process and a raw biogas throughput of 1400 m_n^3/h	Coupling with a biogas plant with on-site electricity generation with a capacity of 2000 kW_{el}
Best-case scenario Wholesale prices for German electricity before the COVID-19 pandemic: 0.05 €/kWh	0.2174 €/kWh_{SNG}	0.2525 €/kWh_{SNG}
Normal-case scenario Taking into account short-term price increases from the war in Ukraine but also expected (further) price reductions: 0.10 €/kWh	0.3399 €/kWh_{SNG}	0.3823 €/kWh_{SNG}

[a] To upgrade biogas to biomethane, CO_2 especially is separated. This is done in a biogas upgrading plant. The separated CO_2 can then be used as an input for producing SNG. In [58], the process depicted (SNG alternative 1) yielded the lowest SNG production costs and is therefore used here

[b] Besides using CO_2 from a biogas upgrading plant, biogas can be used directly for producing SNG, either through biological or catalytic methanation. I used this second scenario alternative, so that I had a comparison to the less common biogas upgrading process. The reported SNG production costs were the lowest derived in [58] for this process and are based upon catalytic methanation

- Concession fee: 0.03 €ct/kWh
- Natural gas tax: 0.55 €ct/kWh
- CO_2 price: 0.455 €ct/kWh
- Labeling costs: 0.05 €ct/kWh
- Value added tax: 19%

For those tariffs in the calculation that contain a mix of renewable and natural gas [49], the costs for natural gas were assumed to be 0.09 €/kWh for the *normal-case scenario* and 0.019 €/kWh for the *best-case scenario* (using spot market prices from 2019 to 2021 for the *best case* and prices from 2021 for the *normal case*; taken from [65]). The combination of these price components allows for calculating end consumer prices that can then be compared to consumer preferences and WTP.

Development of hypotheses

Building on this information and these theoretical considerations, I developed a series of hypotheses. As DCEs ground on the assumption that products are bundles of attributes which generate different utilities for consumers, who try to maximize their personal utility from them [41–43], adding price as an attribute in the choice sets allows for the calculation of utilities derived from price differences, which in turn enables the calculation of tradeoff prices [39]. In other words, if the price attribute is held at zero for all product alternatives, then price no longer factors into the consumer's choice, making it possible to calculate the real aversion. Past research, especially in the field of renewable electricity tariffs, which are the products most similar to the less researched renewable gas tariffs, has shown that consumers prefer renewable-based over fossil-based tariffs [51, 53, 68–70]. Put differently, consumers derive more utility from renewables than from fossil fuels. From these considerations, the first hypothesis can be derived:

H1: Consumers prefer renewable gas over natural gas for residential heating.

If this is so, which renewable energy source do consumers prefer? Again, due to the lack of research in the field of renewable gases, we have to look at its closest analogy, renewable electricity. Kalkbrenner et al. [53], for example, found that consumers in Germany prefer electricity from solar and hydro power over a more diversified mix, including solar, hydro, wind, and biomass. This finding is supported by Danne et al. [70], who found that solar is preferred over wind power and both are preferred over biogas-based electricity. Given that SNG harnesses surplus electricity from renewable energies (especially wind, hydro, and solar) and biomethane uses biomass, these insights might be transferable to SNG/biomethane. However, studies from other national contexts (e.g., [69], Australia) have reported that biomass-based electricity is favored over other renewables; indeed, newer studies from Germany indicate that the previously critical perception of biomass seems to have faded [16, 71]. These considerations, together with the novelty of SNG technology and the consequent consumer knowledge gaps that could intimidate a consumer, yield the second hypothesis:

H2: Consumers prefer biomethane over SNG for residential heating.

By taking into account the price attribute, DCEs allow for the estimation of the WTP values for other attributes as well as their levels within the experiment. They thereby also facilitate comparisons between different shares of renewables in a product. Existing research, again taken from renewable electricity, has found varying additional WTP values. Herbes et al. [68] identified a WTP premium of 15% for a renewable product over a fossil-based one. Kalkbrenner et al. [53] differentiated between consumer groups and found maximum additional WTP for electricity from solar and hydro power to be 12.7% for non-adopter households and 19.3% for adopters (i.e., households owning innovative energy technology-like photovoltaic systems). In their study focusing on different supplier types, Rommel et al. [51] found a maximum WTP premium of approximately 25% for a 100% renewable product that is offered by a municipal utility when compared to a non-renewable tariff offered by an investor-owned company. In the only study focusing on replacing natural with renewable gas, Kim et al. [30] used a contingent valuation experiment in South Korea and found an additional WTP of 32%, which is significantly higher than the aforementioned studies focusing on renewable electricity in Europe. This might lead one to expect a higher WTP; however, German gas market experts highlight "…that consumers have become accustomed to comparably cheap electricity from renewable sources in the electricity market, since green tariffs are often not more expensive or only slightly more expensive than non-green tariffs." [16]. The third hypothesis addresses exactly this topic:

H3: Consumers are willing to accept price increases for SNG.

As shown above, SNG comes with significantly higher production costs than biomethane and especially natural gas [26, 58, 66, 67]. Although I expect consumers to accept price increases (hypothesis 3), I doubt their WTP will be sufficient to cover the higher production costs. Accordingly, the last hypothesis is:

H4: SNG production costs and consumers' WTP do not match; SNG costs are too high to accommodate consumers' WTP.

I examine these hypotheses against the results in the next chapter.

Socio-demographics variables and information on housing and heating

Before turning to the results of the DCE, it is necessary to look at some accompanying variables relating to socio-demographics as well as information on housing and heating. They are summarized in Table 5.

The sample is slightly dominated by men and by participants who are relatively wealthy compared to the national average. Almost 60% of the participants live in buildings more than 30 years old. This means comparably newer buildings are in the sample, as the nationwide share of people living in buildings older than 33 years is 79% [77]. However, the refurbishment status of the buildings indicates more than ¼ are still in their original condition and only 43% are partially renovated. The dominant gas supplier for residential heating is the local basic supplier, 'Stadtwerke', which was originally founded by local authorities to ensure public services and has been an important actor in the German energy market [78]. Almost 60% of the participants have their contracts with Stadtwerke, consistent with the national average [76].

Results

To present the results (especially on WTP and preference share), I follow the ceteris paribus-approach: Only the explicitly mentioned attributes are varied, while all the other attributes (and levels) remain the same. This is to focus the analysis on the priority of this paper: SNG in the residential heating market. Furthermore, as shown in [27], the gas mix, i.e., the share of renewables in the product, is the most important attribute for consumers in their decision-making. Influences from other attributes are, therefore, controlled/extracted.

Table 5 Socio-demographics variables as well as information on the housing, and residential heating of the survey respondents, with a comparison to national statistics

Variable	Values	Sample	National average	Sources
Sex (*n* = 512)	Female	39.6%	50.7%	[72]
	Male	60.2%	49.3%	
	Diverse	0.2%	N/A	
Age (*n* = 503)	Mean	42.19	44.5	[73]
Monthly household income (net, *n* = 512)	Less than 1000€	6.4%	9.7%	[74]
	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	
Construction year of building (*n* = 512)	Before 1969	24.4%	N/A	N/A
	1969 to 1978	11.9%		
	1979 to 1983	10.2%		
	1984 to 1994	12.7%		
	1995 to 2001	17%		
	2002 to 2009	11.3%		
	2010 to 2015	6.8%		
	2016 to 2021	5.7%		
Refurbishment status (only buildings built before 2010, *n* = 448)	Original condition	26.8%	N/A	N/A
	Partial refurbishment	43.1%		
	Conventional refurbishment	21.4%		
	Future-oriented refurbishment	8.7%		
Calculated yearly fuel costs for heating and hot water (€, *n* = 512)	Mean	845.9	820	[75]
Current gas supplier (*n* = 512)	Local basic supplier (i.e., municipal utility)	58.4%	64%	[76]
	Another local supplier	14.6%	N/A	
	National supplier	23.2%	36%	
	Unknown	3.7%	N/A	

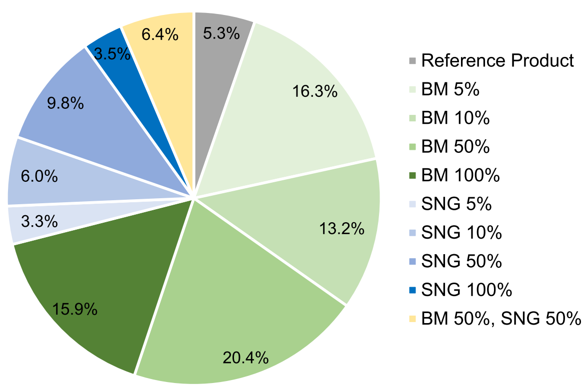

Fig. 2 Preference Shares for 0% price increase

Preference shares

Turning to the question posed by the first hypothesis, Fig. 2 presents the preference shares in an idealized world where no price premia exist. This shows what consumers would choose if they did not have to pay more for a renewables product. The display uses green for biomethane and blue for SNG. Increasing proportions of both are shown by darker colors.

In this fictitious assessment, a small but significant share (5.3%) still prefer natural gas. That almost 95% prefer a tariff with some renewable share, however, demonstrates clear support for Hypothesis 1: Consumers do prefer a renewable share. The fact that almost 2/3 would opt for biomethane, compared to only 23% for SNG products and 6% for the mixed product, demonstrates support for Hypothesis 2: Consumers do prefer biomethane.

Willingness to pay for SNG

The study's central question about WTP for SNG is addressed by Fig. 3, which shows the relative WTP over a 100% natural gas reference product:

Here, the *y*-axis indicates the WTP for the products labelled on the *x*-axis. The depicted SNG products are (ceteris paribus) typical products on the market: They carry a TUEV-label, are not regionally produced, and are offered by a municipal utility. The only variation is their share of SNG. As that increases from 5 to 100%, respondent WTP increases from 40% to 68.7% over the reference product. WTP does increase with rising shares, but whether those WTP increases keep up with rising product costs remains to be seen. Nevertheless, these results support Hypothesis 3: Consumers are willing to pay a premium for SNG.

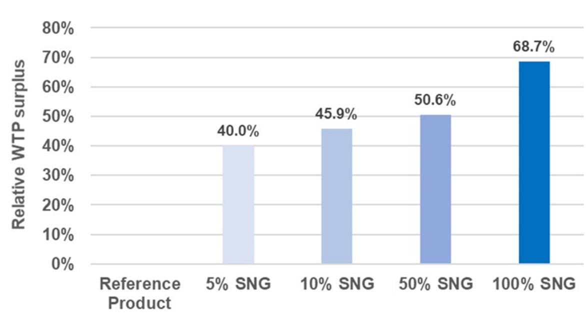

Fig. 3 Relative WTP surplus for SNG over natural gas

Matching SNG production costs with WTP

Do the rising WTP values match rising production costs? Tables 6 and 7 compare the numbers using two SNG alternatives represented vertically. Table 6 presents the *best-case scenario*, and Table 7 shows the *normal-case scenario*. A more detailed scenario description can be found in Table 4 in the Method section. The numbers under each alternative are end consumer prices including production costs and further price components like taxes and sales costs (see Method section).

The first column repeats the previously defined market parameters used for the two scenarios. The consumer WTP is derived by multiplying 1 + the average relative WTP values (from Fig. 3) by the two end consumer prices for natural gas in the heating market.

Tables 6 and 7 highlight the seven cases (of 16) where the consumer WTP covers the costs of production. Only for lower shares of SNG in the product is consumer WTP adequate. These matches are marked in bold. For higher shares of SNG, consumer WTP falls well short. At a 50% share, WTP would need to double, while at a 100% share, it would need to triple to meet production costs. That means that in today's market, only products highly diluted with relatively cheap natural gas match the consumer WTP. Hypothesis 4 is therefore only supported for products containing 50% and more SNG (and for 10% under *SNG-alternative 2* in the *normal-case* scenario). For lower shares of SNG, consumer WTP values matched the product costs.

Discussion

I conducted a DCE to gain an insight into consumer preferences for renewable gases and to calculate the WTP for SNG in the German residential heating market. To this end, I used an online survey to collect 5,632 active choices from 512 participants who use gas for their residential heating. After analyzing these data, I compared the results to SNG production costs in order to assess the degree to which consumer WTP for a SNG product can, or cannot, cover its production cost.

Table 6 Matching SNG consumer prices to end consumer WTP for two SNG alternatives for the *best-case scenario*

Market parameters	Products	Consumer WTP	SNG consumer prices based on different SNG production costs	
			SNG alternative 1: 21.74 €ct/kWh	**SNG alternative 2: 25.25 €ct/kWh**
· 5 €ct/kWh$_{el}$ electricity price for electrolysis · 1.9 €ct/kWh natural gas spot market price · 7.06 €ct/kWh end consumer price for natural gas	5% SNG	**9.88 €ct/kWh**	**7.16 €ct/kWh**	**7.37 €ct/kWh**
	10% SNG	**10.30 €ct/kWh**	**8.34 €ct/kWh**	**8.76 €ct/kWh**
	50% SNG	10.63 €ct/kWh	17.78 €ct/kWh	19.87 €ct/kWh
	100% SNG	11.91 €ct/kWh	29.59 €ct/kWh	33.77 €ct/kWh

Combinations for which WTP exceeds cost are shown in bold

Table 7 Matching SNG consumer prices to end consumer WTP for two SNG alternatives for the *normal-case scenario*

Market parameters	Products	Consumer WTP	SNG consumer prices based on different SNG production costs	
			SNG alternative 1: 33.99 €ct/kWh	**SNG alternative 2: 38.23 €ct/kWh**
· 10 €ct/kWh$_{el}$ electricity price for electrolysis · 9 €ct/kWh natural gas spot market price · 12.21 €ct/kWh end consumer price for natural gas	5% SNG	**17.09 €ct/kWh**	**15.92 €ct/kWh**	**16.17 €ct/kWh**
	10% SNG	**17.81 €ct/kWh**	**17.40 €ct/kWh**	17.91 €ct/kWh
	50% SNG	18.39 €ct/kWh	29.30 €ct/kWh	31.82 €ct/kWh
	100% SNG	20.60 €ct/kWh	44.17 €ct/kWh	49.21 €ct/kWh

Combinations for which WTP exceeds cost are shown in bold

Consumers prefer renewable over natural gas and biomethane over SNG

The results indicate that, with all other influences held constant, consumers derive more utility from renewable than from natural gas, which is in line with other studies, especially in the field of renewable electricity [51, 53, 68–70]. Interestingly, the criticism of biogas—in particular the usage of energy crops, as cited often in the ‘food vs. fuel’ debate—seems to have died down, as respondents favored biomethane over SNG. This finding concurs with other studies which have found that the public perception of biomass has become more favorable in recent years. First indications of this shift were reported in [16] based on interview data from 2020 and thus before the Russian invasion of Ukraine. The shift was confirmed in [71] by a representative online survey in autumn 2022, which took into account the energy crisis and its effects on the public perception of bioenergy.

Another potential explanation for my finding regarding the preference for biomethane lies in the DCE itself. SNG products partly came with substantially higher prices (see Table 3). During the completion of the choice tasks, an anti-halo effect might have occurred as respondents saw SNG products with comparably high prices, making them quick to refuse these products during the next choice tasks.

My findings on heating fuel preferences for residential heating if there were no increase in the tariff price may seem counterintuitive. After all, if a consumer can have a 100% share of biomethane or SNG in their tariff for the same price they pay for natural gas, why not opt for this every time? The answer most likely lies in the design of the DCE itself: Since DCEs are supposed to show all attributes and levels equally often, the participants were not always presented with a 100% share in the choice set. Still, the results indicate consumer preferences at work that bear further investigation.

Consumers have a surprisingly high WTP for SNG

Consumers clearly expect to pay more for SNG. I found a surprisingly high initial WTP of 40% for only a 5% share of SNG, indicating that consumers value this new technology and expect it to come at a higher price. Here we can credit the design of the DCE, as the price increase levels were based on the SNG prices identified in [58]. This means participants were not confronted with unrealistic price increases but could evaluate realistic choices. It also revealed that consumer WTP tops out at just under 69% for the 100% SNG product. And while WTP values would have to double and triple to cover 50% and 100% SNG content, respectively, respondents nonetheless appear ready to bear substantially higher costs for SNG in their heating mix.

Hence, the results challenge the idea raised in [16] that consumers have grown used to minimal price surpluses for renewable over conventional energy. Compelling evidence that consumer WTP has changed is found by comparing the relatively high WTP for SNG to the lower WTP for renewable electricity – as seen, for example, in [51, 53, 68], three studies that predate both the pandemic and the war in Ukraine. The WTP values for SNG in this study can be compared to Kim et al. s' 2020 finding [30] of a 32% WTP for biomethane- over natural gas-based heat in Korea. Those results point to a comparably higher WTP for renewably-sourced heating fuel, although in Kim et al. s' case, the renewable product is from a different technology, in another national setting, and based upon a different methodological approach.

Consumer WTP covers only a small share of the production costs

The relatively narrow range of WTP premia exhibited by respondents—40 to roughly 70%—covers production costs only for products in the lower range of SNG shares (5% and 10%); it does not come close to covering costs for 50% and 100% shares. That means that there is an opening for marketers to sell SNG in the voluntary heating market, which might allow SNG prices to come down. And they would have to come down considerably, as it is unlikely that consumers will be willing to pay between 30 and 50 €ct/kWh for a 100% SNG product.

Furthermore, the positive differences between WTP and the costs of lower share tariffs leave some room for changing market conditions as well as for profit margins, which have not been considered as a price component in the SNG alternatives. This logic of replacing fossil components partially with renewable and more sustainable alternatives can also be found in other consumer products: e.g., peat-reduced gardening substrates, where climate-damaging peat is replaced partially with renewable-based alternatives like wood fiber or compost. These products also come with modestly higher prices, so the partial replacement strategy provides flexibility on both the consumer and production sides: the former in willingness to pay higher product prices, the latter in willingness to pay higher production costs.

Against this backdrop, it comes as no surprise that the only available gas tariff containing renewable gas stemming from PtG technology (though not from SNG, but from its precursor, hydrogen, which can to a certain degree be injected directly into the natural gas grid) contains only around 1% of this gas and a share of at least 15% of the significantly cheaper biomethane. The target for 2024 is a 35% share of renewable gases [79].

The latest data on gas for the heating market [80] show that prices have decreased, both in the spot market and at the consumer end point; however, current levels still make the *best-case scenario* look quite optimistic. Therefore, the *normal-case scenario* can and should be considered most realistic in the short- to mid-term. Furthermore, given that electricity prices are the main cost drivers for hydrogen and SNG production [26, 58, 66, 67], the two markets experience high volatilities that demand close monitoring [81].

Because consumer WTP only accounts for smaller shares of SNG, the pertinent question concerns how the currently expensive production of SNG can and should be financed. To gauge consumer sentiment, a question was included in the survey to solicit respondent preferences for one of four different financing mechanisms: (1) direct financing via the retail price; (2) a tax/levy on fossil fuels; (3) a tax/levy on all fuels; or (4) financing via the general governmental budget, i.e., tax-based. The results revealed no strong consumer preferences, as the neutral answer option was most often selected for all four financing choices. That said, tax-based (mean = 3.24, measured on a scale from 1 to 5, n = 512) and direct financing via the retail price (mean = 3.13) were slightly favored over a levy on fossil fuels (mean = 2.89) or on all fuels (mean = 2.88). This can be read as consumers preferring financing mechanisms that do not add costs to their regular bill. This result is in line with Tröndle et al., who analyzed a slightly different topic (policy measures in the residential building sector) but got similar results: Consumers tend to reject measures that result in additional costs, like a purchase tax or taxes on fossil fuels [82].

Limitations and further research

The presented results should be considered against the energy market developments following the Russian invasion of Ukraine. I conducted the DCE in the summer of 2021, almost 6 months before the invasion, which has led to a spike in energy prices and higher inflation. These have affected the daily lives of poorer households especially [83]. What does this mean for the preferences and WTP values in this study, then? On the one hand, renewable gases do not need to be imported, meaning they lower import dependencies and generate a national/regional added value. As these are all factors positively valued by consumers [71], one could anticipate positive effects on WTP. On the other hand, increased energy prices due to new sourcing, other price components like an increasing CO_2 tax, and reduced purchasing power due to inflation could depress WTP and the willingness to spend money on what may seem a luxury—i.e., renewable gas shares in one's residential gas tariff—especially since this is a product that merely has to fulfill the basic requirement of uninterrupted heating in winter. These factors call for further studies that take into account WTP for renewable gases and therefore measure the effects of the war in Ukraine. This could and should also cover changes in perception toward biomass-based energy in more detail.

In addition, the political requirements in Germany changed at the beginning of 2024 when the (controversial, see [9]) amendments to the Building Energy Act came into force, which include a 65% renewable heat requirement for new residential buildings. Biomethane and SNG could be used to meet this requirement. Further studies could take this into account, considering not only the fuel costs but also the investment costs for heating systems, as different renewable alternatives need to be compared in the decision-making process.

The selection of the two alternatives used for SNG production costs (taken from [58]) were based on the criteria of efficiency and representativeness. Further studies could investigate other technology combinations and examine other assumptions regarding costs and prices to enlarge the body of literature on SNG.

It came as a surprise that consumers showed a comparably high WTP for SNG. This is partly due to the stated preference approach of the DCE, whose simulation of the decision situation in an anonymized online setting allowed participants to exhibit a higher WTP. This finding could be cross-checked via a laboratory experiment where participants bid real money on different tariffs that are presented in a real market setting, i.e., on homepages or leaflets. This would also diminish the effects of decomposing the study object (renewable gas for heating tariffs) into different attributes and their levels, which is quite abstract compared to the format of market offerings, even if it is common practice in DCEs.

Conclusions

This study arose in response to the observation that on its current trajectory, the German residential heating sector set to fall far short of its long-term climate goals. The study was to determine, first, whether a consumer preference for renewably sourced heating fuel existed and if so, how it can be characterized. Second, and principally, the study sought to determine consumer WTP for SNG mixtures in heating fuel tariffs and compare this to production costs. SNG is an innovative approach that uses surplus electricity from renewable sources, such as solar or wind power to generate hydrogen, which can then be upgraded to SNG using CO_2 (e.g., from a biogas upgrading plant) in a methanation plant.

To explore these aspects, I conducted a DCE with 512 respondents. This study is the first of its kind in a European context, as well as the first globally to examine both the production and consumption of SNG. As such, it can guide both policy- and entrepreneurial decision-makers in the daunting transformation process of the residential heating sector toward climate neutrality. The guiding research questions can be answered as follows:

> *RQ1: How much are consumers willing to pay for different shares of SNG in their residential heating gas tariff?*

Consumers show a surprisingly high WTP for increasing shares of SNG: 40% for a 5% SNG share, 45.9% for 10% SNG and 50.6% for 50% SNG, and almost 70% for a 100% SNG tariff over a natural gas-based tariff.

> *RQ2: How does the cost of producing SNG compare with consumer WTP in the residential heating market?*

Only for tariffs with small shares of SNG (5% and 10%) do consumers' WTP exceed production costs and could therefore be offered at cost-covering prices. For higher SNG shares (50% and 100%), the production costs exceed the WTP of consumers and therefore such tariffs would not be economically viable.

Given that an alternative to SNG, namely biomethane, is already available in the market [49] and is both less expensive to produce and, as presented, preferred by consumers, marketers should consider carefully whether it is worth them offering SNG as a product in the residential heating market. If they decide to do so, tariffs with low shares of SNG (5% and 10%) are the only suitable ones as these shares alone match consumer WTP. Past research has shown that the voluntary market for renewable gases is driven by legal obligations, resulting in 10% biomethane tariffs being dominant. This is mainly because one federal state (Baden-Wuerttemberg) has specific regulations on renewable heat and allows a maximum biomethane share of 10% [49]. This matches the consumer WTP for SNG identified in this study. An especially interesting target group would be tenants with little influence over other aspects of their heating system (e.g., exchange of heating technology) or efficiency measures (like retrofitting buildings), as their tariff selection could be their only option to support renewable heating.

The results open a broader discussion about the residential heating sector and its need for a substantial transformation to achieve climate neutrality within 20–25 years. That need cannot be met via voluntary gas tariffs with a 5–10% share of SNG—even though SNG emits less CO_2 and could be used in existing and enduring infrastructure, such as the natural gas grid and existing gas boilers. Here, SNG and especially biomethane can act as short-term transition fuels while other approaches like efficiency measures, the exchange of heating systems (e.g., fitting more efficient and cheaper heat pumps [84]), and the provision of more centralized heating help to prevent long-term lock-in to fossil and natural gas-based heating [85]. Provision for SNG (as a hydrogen derivative) in current policymaking, such as through the German Building Energy Act, should be carefully reconsidered as a compliance option for achieving climate neutrality in residential heating. Despite recent technological progress, efficiency losses occur throughout the SNG production process [86], making it an expensive product to be used in sectors and applications that are not suitable for direct electrification, like road freight, shipping or industry segments, which rely on carbon molecules for their production [87].

Abbreviations

Bio-SNG	Substitute natural gas from biomass
CO_2	Carbon dioxide
DCE	Discrete choice experiment
€	Euros
€ct	Euro Cents
EU	European Union
GGL	Green gas label
HB	Hierarchical Bayes
kWh	Kilowatt hour
MWh	Megawatt hour
m^3	Cubic meter
m_n^3	Standard cubic meter
PtG	Power-to-Gas
RQ	Research question
SNG	Synthetic natural gas
WTP	Willingness to pay

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Availability of data and materials
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Declarations

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Not applicable.

Consent for publication
Not applicable.

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The author declares that he has no competing interests.

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