Renewable gases fueling the energy transition in residential heating and private transportation: A multi-perspective approach

Dissertation

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Benedikt Rilling

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Erstgutachterin: Prof. Dr. Jale Tosun
Zweitgutachter: Prof. Timo Goeschl, Ph.D.

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List of Abbreviations

AFV	Alternative Fuel Vehicle
Bio-CNG	Biological Compressed Natural Gas
Bio-SNG	Substitute Natural Gas from Biomass
BM	Biomethane
CHP	Combined Heat and Electrical Power
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalents
DCE	Discrete-Choice Experiment
E10	Petrol blended with 10% ethanol
€	Euro
€ct	Euro-cent
eq	Equivalent
EEG	Renewable Energy Sources Act (Erneuebare-Energien-Gesetz)
EU	European Union
EWärmeG	Renewable Heat Act (Erneuerbare-Wärme-Gesetz)
EX	Expert
FG	Focus Group
FIT	Feed-in-Tariff
GEG	Building Energy Act (Gebäude-Energie-Gesetz)
GGL	Green Gas Label
GHG	Greenhouse Gas
GWH	Gigawatt-hour
HB	Hierarchical Bayes
IEA	International Energy Agency
IP	Interview Partner
JRC	Joint Research Center
kWh	Kilowatt-hour
kWh_{el}	Kilowatt-hour electric
LNG	Liquified Natural Gas
m^3	Cubic meter
MJ	Megajoule

MNL	Multinomial Logit Model
MOAM	Motivation-Opportunity-Ability Model
Mtoe	Million Tonnes of Oil Equivalent
MW	Megawatt
MWh	Megawatt-hour
N/A	Not available
NAM	Norm Activation Model
NGO	Non-Governmental Organization
PtG	Power-to-Gas
RED	Renewable Energy Directive
RESA	Renewable Energy Sources Act (EEG)
RFNBO	Renewable Fuels of Non-Biological Origin
RHI	Renewable Heat Incentive
RLH	Root Likelihood
RQ	Research Question
SD	Standard Deviation
SNG	Synthetic Natural Gas
SWOT	Strengths, Weaknesses, Opportunities and Threats
TPB	Theory of Planned Behavior
TWh	Terawatt-hour
UK	United Kingdom
VBNM	Value-Belief-Norm Model
WTP	Willingness-to-pay

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1) Introduction

The transition toward a low-carbon energy system is one of the most urgent challenges of the 21st century. Nations around the world are working to meet three key objectives in their energy policy: to achieve ambitious climate targets; to ensure energy security and enhance economic competitiveness; and to ensure affordability, which is paramount for poorer households in the context of energy poverty (Heffron et al., 2015; Tosun, 2023b). Balancing those three poses a significant challenge to policymakers, as became particularly evident following the outbreak of war in Ukraine in 2022 and the subsequent energy crisis (Kuzemko et al., 2022; Steffen & Patt, 2022). Germany, a global frontrunner in the energy transition, has made significant progress in reducing greenhouse gas emissions and increasing the share of renewable energy sources in its electricity production: The share of renewable energies in gross electricity generation in Germany has been steadily growing over the past 30 years, reaching 54.1% in 2023 (BDEW, 2024).

However, achieving a fully decarbonized energy system requires more than just a shift in electricity generation (Geels et al., 2017). It also necessitates the transformation of other sectors, such as industry, transportation and heating, which remain heavily reliant on fossil fuels and lag behind their sectoral targets for emissions reduction. Despite some progress, the German transportation and heating sectors have not met their individual targets for three and four years in a row, respectively (Geschäftsstelle Expertenrat für Klimafragen, 2024). In this regard, one fossil fuel plays an important yet ambivalent role: natural gas. Almost a quarter of Germany's primary energy consumption is met by natural gas. In 2023, the most important sectors for natural gas sales were industry (34.3%), private households and housing companies for heat generation (31.9%), and with almost equal shares (approximately 13%) trade, commerce and services as well as electricity generation. In transportation, natural gas plays a small yet notable role (BDEW, 2024). Its ambivalence manifests itself in multiple ways: The development of natural gas infrastructure over several decades has resulted in the creation of systematic (path) dependencies on this energy source and its suppliers. Given that Germany is only able to self-supply a limited proportion of its needs, it has historically relied on gas imports from Russia. However, this situation changed rapidly following the Russian invasion of Ukraine in 2022, which led to the cessation of imports. Germany and other European states have since demonstrated the ability to rapidly identify alternative sources and develop new means for importing natural gas (Halser & Paraschiv, 2022; Moskalenko et al., 2024). This comes as no surprise, given existing gas infrastructures, path dependencies and the imperative to fulfil the imperative to ensure the security of supply. Furthermore, natural gas was considered a safe and cost-efficient option prior to the war in Ukraine (Scharf et al., 2021) and remains a potential bridge technology on the path towards an energy system that is entirely reliant on renewable sources (Deutscher Bundestag, 2022; Wiertz et al., 2023). The primary rationale for its deployment lies in its lower emissions compared to coal and oil (a marketing claim used frequently; see Schmid-Petri &

Elschner (2024)), the flexibility it offers in accommodating fluctuating renewables in electricity generation, and, in the long term, the potential for its replacement with green hydrogen. However, this "ability" to act as a bridge technology is contested by numerous researchers, who have identified a range of challenges, including methane emissions, infrastructure lock-ins, stranded assets, crowding-out effects of low-carbon technologies, and behavioral lock-ins (Brauers, 2022; Brauers et al., 2021; Fouquet, 2016; Gürsan & De Gooyert, 2021; Kemfert et al., 2022; Seto et al., 2016).

To illustrate the complexity of this problem, we may consider a real-life example: In 2023, sales of (residential) heating systems in Germany reached a 30-year high, with 1.3 million units sold, representing a 34% increase compared to the previous year. This can be split into two time periods and explanations: In the first half of the year, manufacturers recorded a sustained boom in demand for heat pumps. One reason was the war in Ukraine and consumer concerns from 2022 about a possible gas shortage. In the second half of the year, the controversial debate surrounding the amendment to the German Building Energy Act (GEG) and the future subsidy framework (Kern et al., 2023) led to the complete opposite: The demand for the modernization of gas and even oil heating systems increased, while the sales of heat pumps plummeted. Over the course of 2023, around 800,000 gas-based heating systems were sold, whereas the figures for the preceding years stood at approximately 600,000, with a declining tendency (BDH, 2024b, 2024a). This example serves to illustrate four key points: Firstly, it underlines the importance of the steering effect of policymaking (Geels et al., 2017). Secondly, it demonstrates the unintended and even contradictory effects that can result from policymaking that fails to adequately consider public opinion and preferences. Thirdly, it illuminates the scale of the task at hand and shows that successful energy transitions require alignment, support and corresponding action from stakeholders besides policymakers. Lastly, given the long lifespan of installed infrastructure, it highlights the continued importance of natural gas in the energy system (Scharf et al., 2021).

In this context, renewable gases, including biomethane and synthetic natural gas (SNG), have emerged as critical components of a broader energy transition, offering a sustainable alternative to conventional natural gas. Since their chemical properties are identical to those of natural gas, they can be used as a drop-in solution and direct substitute for fossil natural gas in the short- to mid-term (Horschig et al., 2018; IEA Bioenergy, 2022; Kolb et al., 2021a, 2021b). Consequently, renewable gases could contribute significantly to solving the complex problem of gas dependencies and long-living infrastructure. In fact, Marconi and Rosa (2023) found that biomethane had the potential to offset almost 30% of the global natural gas demand in 2019. The International Energy Agency (IEA) (2021) anticipates that the proportion of global grid supply derived from renewable sources will increase from a currently negligible level to more than 30% by 2050. The largest contribution, approximately 21%, is projected to originate from biomethane, followed by SNG with approximately 10%. An additional 4% is expected to come from hydrogen.

Estimates show that if Germany realizes the potential of biomethane and SNG, up to 25% of its natural gas demand in 2022 could be met with renewable gases (Hansen et al., 2022). Matschoss et al. (2020) elaborate on this in greater detail in their scenario analysis. They find the domestic potential of biomethane to be between 11 and 54 Terawatt-hours (TWh) in 2030 and between 7 and 113 TWh in 2050; for SNG these numbers are 0-83 TWh in 2030 and 3-681 TWh in 2050. Transferring their average supply values (24.9–32.5 TWh for biomethane and 41.5 TWh for SNG) to the natural gas demand of 813 TWh in 2023 (AG Energiebilanzen e.V., 2023), the share of renewable gases would stand at between 8.2 and 9.1%. The high ranges, particularly for SNG and for the longer time horizon, indicate that these scenarios should be approached with a certain degree of caution. Still, we can conclude that renewable gases will constitute a component of future energy systems, and thus warrant further investigation.

Existing research focuses on the supply side especially, examining different methanation technologies, production capacities, or prospective scenarios for the future relevance of renewable gases (Kolb et al., 2021a; Krupnik et al., 2022). Minimal attention has been paid to the demand side, specifically consumers and their decision-making. Nevertheless, a more profound understanding of these elements is of paramount importance for transformation processes as well as for the adequate and effective design of corresponding policies and markets (Creutzig et al., 2018; Fonseca et al., 2019), particularly in light of the anticipated significance of renewable gases in future energy systems (IEA Bioenergy, 2022; Radosits et al., 2024). This cumulative dissertation contributes to this body of literature by analyzing the overarching research question of how renewable gases can successfully contribute to an energy transition beyond electricity, especially in the residential heating and private transportation sectors – two markets for (renewable) gases in which consumers can actually decide according to their preferences (unlike the markets for electricity generation or industrial usage, for instance). How exactly renewable gases can contribute is considered from three perspectives: from the consumer, the supplier, and policymaking.

The five articles of this cumulative dissertation can be categorized in two ways: The first concerns the markets analyzed, the second the actors and contexts analyzed. The first article looks at the heating market and provides an analysis of relevant biomethane policies and (tariff) offerings to private consumers in Germany, the United Kingdom (UK), Austria, and Switzerland. More precisely, the policy analysis offers insights into the prioritization of markets and the impact of policy on the heating market supply for private consumers. The tariff analysis demonstrates how consumer preferences are reflected in those offerings and how policies influence the design of renewable gas products. The second article shifts the perspective and presents an analysis of the decision-making context of consumers in the heating market and their perception of renewable gases for heating. It then validates this with the opinions of gas market experts on their customers. The third article extends this analysis to consider consumer preferences for renewable heating tariffs. The foci of both articles (2 and 3) target a notable gap in the existing literature, as the preferences of consumers for renewable electricity have been widely examined, yet the same is not true for renewable gases in residential heating. Partially building on the same dataset, the fourth article compares the willingness-to-pay (WTP) for SNG in residential heating to its production cost, revealing a (mis)match. This insight is significant for the ongoing and recent debate on synthetic and e-fuels. The fifth and final article of this dissertation employs a comparable empirical methodology to that used in the third article but shifts the focus onto consumer preferences for renewable gases in a different market segment, namely private transportation.

The remainder of this introduction provides further empirical insights and an overview of the concepts central to this dissertation, namely the technologies and policies for renewable gases. Subsequently, I sketch the theoretical rationale guiding this dissertation. I then present a summary of the (empirical) findings of the five articles that form the basis of this dissertation. Finally, I discuss those results, highlight their contribution to the literature and identify directions for further research.

1.1 Empirical background

The focus of this dissertation is not the decision-making processes associated with technology adoption and larger investments in transportation and residential heating solutions, such as retrofitting existing buildings, installing new heating systems with enhanced energy efficiency or purchasing alternative fuel vehicles. These solutions can be considered long(er)-term and more disruptive (Thomas et al., 2023) and have been extensively examined in the existing literature, with comprehensive literature overviews provided in articles 4 and 5. This distinction is especially relevant for the decision-making context, as these solutions classify as high-involvement decisions, that is, consumers tend to evaluate decisions meticulously and invest much time and effort when deciding which new heating system or car to buy, for instance (Foti & Devine, 2019; Yoo et al., 2020). The fuel and gas going into those infrastructures or products are the focus of this dissertation and are, in contrast, considered as low-involvement products, as consumers usually limit the amount of time and effort they invest before reaching a decision over them. Consumers also tend to have a high price sensitivity toward them (Friege & Herbes, 2017) and stick with their decisions once they have made them. In fact, only 8.2% and 8.9% of residential customers in Germany in 2022 switched their suppliers for electricity and gas, respectively (Bundesnetzagentur & Bundeskartellamt, 2023).

Given the limited research available and the chemical properties of renewable gases, particularly their ability to directly substitute natural gas in a number of applications, two “close relatives”, namely renewable electricity and mobility research, provide valuable insights for this dissertation and can be reasonably transferred to the analysis of renewable gases. In this context, several studies analyzing the German electricity market and consumer preferences found that biomass and biogas are the least preferred renewable energy sources for German consumers (Bengart & Vogt, 2021; Danne et al., 2021; Kaenzig et al., 2013; Kalkbrenner et al., 2017). A similar conclusion can be made with regard to motorized private transportation: German motorists prefer electricity-based fuels and show considerable aversion toward biomass-based fuels, in both academic surveys (Linzenich et al., 2023) and real life (Tosun, 2017). The underlying reasoning for this is complex. One significant concern, especially among motorists, is the potential technical incompatibility of biomass-based fuels in their vehicles (Tosun, 2017). On a more general level, biomass-based fuels are often negatively associated with land use (changes): As they require more land surface to produce one unit of energy compared to fossil energies, consumers express concerns related to ecological aspects (e.g., wildlife habitats) and the visual quality of landscapes. An additional aspect concerns land use competition, since no food can be grown in areas where biomass is cultivated for energy use. This conflict is often referred to as the “food vs. fuel” debate and is closely connected to fears over rising food prices (Bengart & Vogt, 2021; Danne et al., 2021; Jordan et al., 2023; Kaenzig et al., 2013; Kalkbrenner et al., 2017; Linzenich et al., 2023; Tosun, 2017). All these reservations are especially relevant with regard to concerns over “maizification” (Herbes et al., 2014), with maize remaining the most important feedstock for producing biogas and biomethane in Germany (FNR, 2024; Reinholz & Völler, 2023). The results of a more recent study conducted in Germany suggest that the previously critical perception of biomass may have diminished, especially in the context of the Russian war in Ukraine (Agentur für Erneuerbare Energien, 2022). Furthermore, biomass-based energy is regarded favorably by consumers, particularly when compared to fossil fuels, thanks to its comparatively less detrimental effects on the environment, climate, air quality, and human health. Additional benefits include their potential for job creation, the assurance of a reliable supply, and their potential to reduce reliance on imported resources (Bengart & Vogt, 2021; Danne et al., 2021; Kaenzig et al., 2013; Kalkbrenner et al., 2017; Linzenich et al., 2023; Menges & Beyer, 2017; Tosun, 2017). While a direct comparison of renewable gases and renewable electricity is certainly informative, particularly in the context of residential usage, it is important to highlight two important differences. Firstly, renewable electricity tariffs have existed for almost 30 years, having been on offer to consumers since the mid-1990s (Hast et al., 2015; Wüstenhagen & Bilharz, 2006), and therefore energy companies have had more time to penetrate markets and raise consumer awareness. In 2023, 42% of residential customers had voluntarily opted for a renewable tariff (Bundesnetzagentur & Bundeskartellamt, 2023). By contrast, the market entry of biomethane, as one renewable gas option, came almost ten years later, with the first power plant feeding small amounts into the grid from 2006 onwards (FNR, 2012). Since then, the market uptake has been relatively limited: In 2021, the share of renewables utilized for heat generation was just 16.5%. The contribution of biomethane to this was minimal, accounting for just 2% of the total renewable share (Hansen et al., 2022). Renewable gases, especially biomethane, are therefore the younger and less established technology. The second important difference with renewable electricity is the price: Tariffs containing 100% renewable electricity can be sourced without significant extra costs compared to other tariffs (Bundesnetzagentur & Bundeskartellamt, 2023), whereas the additional costs for a heating tariff with 100% biomethane vary depending on location and availability. The average price is 0.15 € per Kilowatt-hour (kWh), with a surcharge of approximately 100% compared to natural gas (Weigl, 2024). Final costs depend on factors like living space, construction year of the building and its refurbishment status. Still, households have to bear significant extra costs if they want to switch from fossil fuels to renewable gases. The mechanisms in the mobility market, where biomethane is sold as Bio-CNG (Biological Compressed Natural Gas), are entirely distinct from that: 96% of the filling stations offering CNG (Compressed Natural Gas)-fueled vehicles provide only Bio-CNG, which is sold at a lower price than fossil CNG (gibgas, 2024). The underlying reasons and mechanisms are presented and discussed in article 5.

Existing research explicitly addressing consumer preferences and renewable gases is scarce: Two studies focusing on France and Germany revealed significant gaps in knowledge, as well as a preference for biogas derived from agricultural residues and waste over gas from energy crops (forsa, 2012; Herbes et al., 2018b). In a comparative study of consumers in the US, France and Germany, Herbes et al. (2018a) examined perceptions of biomethane as a raw material for bio-based packaging. They found the aforementioned concerns over biomethane, and it accordingly ranked lowest of the tested materials. Turning to consumer WTP for renewable heat, I could only find two studies on the topic, both from South Korea. In their analysis, which was conducted independently of installed heating systems, Kim et al. (2019) determined that households would be willing to accept a 5% price premium for renewable over fossil heat. This insight was refined by Kim et al. (2020) who found a WTP of 32% for heat generation from biomethane over natural gas. It should be noted that research on SNG is lacking. However, Thomas et al. (2023) have conducted valuable research on one of its sources (hydrogen), its usage for heating in the UK and on consumers' perceptions. Their findings indicate that while hydrogen is perceived as less disruptive in terms of the physical upgrades needed (like retrofitting buildings), there are significant concerns over the financial implications of switching to hydrogen, especially with regard to long-term costs. The necessary transition period (i.e., the conversion of boilers and the gas network to hydrogen) and related uncertainties were identified as particularly critical. The study ultimately concludes that while hydrogen may appear to offer a less disruptive technical solution, it still presents substantial challenges, particularly concerning affordability and social acceptance, which could impede its widespread adoption. This result aligns with the findings of Gordon et al.'s (2022) analysis on public attitudes toward domestic hydrogen use. Their review concludes that the public perception of hydrogen is currently unfamiliar and neutral, driven by knowledge gaps and cost concerns.

This can be complemented with insights from a policy preference perspective. Generally speaking, perceived fairness and effectiveness as well as concerns about climate change are the most important determinants of public support for climate policy measures (Bergquist et al., 2022), especially when policy packages include ancillary measures like information campaigns or test phases (Wicki et al., 2020). These insights also translate to the phaseout and replacement of fossil fuels in both of the markets relevant for this dissertation, i.e., residential heating and mobility.

Tröndle et al. (2023) investigated public preferences for policy packages aiming to phase out internal combustion engine vehicles and fossil fuel-based heating systems in Germany. They found that respondents prefer regulatory instruments (such as bans) in the heating market, while market-based instruments (like taxes) are favored in the mobility market. (Public) funding instruments were shown to significantly increase the acceptability of the proposed policy packages. Furthermore, participants who were more concerned about climate change and possessed more comprehensive knowledge of emissions were more supportive of earlier phaseouts and stricter measures.

In conclusion, the existing literature on renewable gases indicates that consumers exhibit a certain reluctance toward biomass-based energy. They tend to favor less disruptive solutions that can be integrated seamlessly and without technical issues into existing systems, and that are affordable. Furthermore, consumers seem not to devote significant attention to the selection of these products, which can explain the existing knowledge gaps. Conversely, knowledge is considered a crucial factor for forming favorable assessments.

1.2 Overview of central concepts

This section provides a brief overview and definition of the main concepts relevant to this dissertation. All five articles deal with renewable gases, therefore an introduction to the underlying technologies and processes is necessary. There are three main, distinct means of producing direct substitutes for natural gas:

- *Substitute natural gas* from biomass (Bio-SNG) is produced from lignocellulosic materials, such as wood or straw, by converting them into syngas. This syngas undergoes purification, methanation, and further refinement. However, the technology remains in the early stages of commercialization and is currently limited to demonstration projects (Kolb et al., 2021b). Therefore, this approach to substituting natural gas is not further analyzed in this dissertation.
- *Biomethane* (Bio-CNG when used in transportation) is the most established form of renewable gas and is produced through the anaerobic digestion of biomass such as energy crops, manure or waste, which generates biogas. This biogas is typically used to produce electricity and/or heat, which are the most common applications (Dotzauer et al., 2022). In 2023, Germany had 9,909 biogas plants with a combined electrical capacity of 5,905 Megawatt (MW) (Fachverband Biogas, 2023). By separating CO_2 (Carbon Dioxide) and other gases from the biogas, it can be upgraded to biomethane. This biomethane is a direct substitute for natural gas and can be integrated into the existing infrastructure (Thrän et al., 2023). In 2023, 248 biogas plants in Germany were injecting biomethane into the gas grid (Fachverband Biogas, 2023). Energy crops, particularly maize, account for 80.9% of the energy-related feedstock used for biomethane production in Germany. This is followed by manure (10.1%) and waste/other residual materials (9.0%). In 2022, the total

sales of biomethane in Germany exceeded 11 TWh, representing a slight increase over the annual domestic production of biomethane. Consequently, its importation is becoming a significant factor in the renewable gas market (Reinholz & Völler, 2023). In 2022, the most significant outlet market for biomethane was electricity generation, which benefitted from a feed-in-tariff under the Renewable Energy Sources Act (EEG), with a total of more than 8 TWh. This was followed by the transport sector, which accounted for slightly over 1 TWh, and heat generation, which accounted for slightly under 1 TWh. The prospective increase in CO_2 pricing on fossil fuels is expected to enhance the competitiveness of biomethane compared to natural gas (Reinholz & Völler, 2023).

- *SNG* (in some cases also described as e-methane or electric natural gas), in comparison to biomethane, is a newer and less developed technology. It utilizes electricity to produce hydrogen, which can then be converted into methane using CO_2. Depending on its origin, it can be fossil-based, partially renewable or fully renewable (see Figure 1-1, European Biogas Association (2024)). This dissertation explicitly focuses on the top-right corner: fully renewable SNG, based on Power-to-Gas (PtG), utilizing excess renewable electricity to produce green hydrogen. The hydrogen can then be converted into SNG by combining it with CO_2 (e.g., from biogas upgrading) through methanation (European Biogas Association, 2024). As the amount of renewable energy in the grid increases, PtG and SNG offer temporary energy storage solutions and are viewed as medium-term alternatives to natural gas in various sectors (Kolb et al., 2021a; Vega Puga et al., 2022). Therefore, PtG and hydrogen-based solutions like SNG are considered essential for fully renewable energy systems (Kolb et al., 2021b; Marocco et al., 2023). However, given the number of process steps in SNG production, it is criticized for efficiency loss (Böck, 2024). With 14 SNG plants in operation in 2023 and a total production capacity of 68 Gigawatt-hours (GWh) per year, Germany had the largest portfolio of SNG plants in Europe (35 plants). In the upcoming years, growth in Europe is expected to be driven especially by France, Finland and Germany. Almost all (98%) of the plants operated or planned in Europe are fully renewable. In terms of production capacity, there has been a notable increase in Europe, with figures rising from 20 GWh/year to 449 GWh/year between 2015 and 2023. It is projected that production capacity will reach 3,000 GWh by 2027, with Finland experiencing a particularly pronounced growth in this period. While a large share of

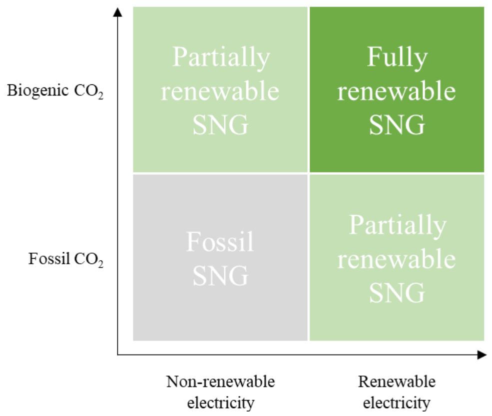

Figure 1-1: Categorization of SNG

plants are still on a pilot or demonstration scale, more and more industrial scale plants are being built, indicating market uptake and development (European Biogas Association, 2024).

This dissertation, therefore, focuses on biomethane and renewable SNG, which represent the most important current substitutes and probably the most promising additional future substitutes for natural gas (International Energy Agency, 2021). Typically, renewable gases (especially biomethane) are not delivered physically to consumers, they are injected into the existing (mostly natural gas) grid. A mass balancing system is used to ensure that the input and offtake of renewable gases is properly documented and balanced (dena, 2024).

This development is accompanied and being driven by relevant policies and other frameworks at the European Union (EU), federal and state levels to promote renewable gases as part of broader climate and energy objectives. These measures play a crucial role in reducing greenhouse gas emissions, increasing energy security, and transitioning away from fossil fuels. I shall briefly outline and describe the most important of those. The *European Green Deal* from 2019 represents the overarching strategy that will guide the EU on its trajectory toward climate neutrality by 2050. It delineates a comprehensive set of ambitious targets for the decarbonization of all economic sectors, encompassing energy, transportation, and industry (European Commission, 2019) and is considered to increase the tempo and scope of climate policy compared to previous policy measures. Its novelty lies in (partially) breaking with old patterns, especially in respect of negotiating emission reduction targets, advancing adaptation policies (besides mitigation policies) and mainstreaming climate governance through an integrated approach to other policy fields such as agriculture and food, finance or social policy (Dupont et al., 2024; Tosun, 2023a; Wolf et al., 2021). With regard to energy, binding policy actions are endorsed and supported by stakeholders (i.e., non-governmental organizations (NGOs), consultancies and industry), but differentiated: Ringel et al. (2021) found a strong focus on energy efficiency targets and measures, with less emphasis on the further development of the framework for renewable energies. As for public support, Baute (2024) found that German citizens clearly favor policy packages supporting the development of the renewable energy sector, especially if they include social policy measures and financing mechanisms at the expense of wealthier persons. The *Fit for 55* package from 2021 substantiated the Green Deal objectives through a series of measures and regulations centered on realizing the 2030 target of 55% greenhouse gas (GHG) emissions reduction compared to 1990. Regarded as a pivotal foundation for renewable gases, it envisions achieving the 55% target primarily through renewables, by enhancing energy efficiency and by meeting more ambitious interim targets on the path toward climate neutrality (Dupont et al., 2024; European Parliament, 2024). For example, one component of this package, the revised *Renewable Energy Directive (RED III)* from 2023, sets a target of 42.5% for the share of renewables in energy consumption by 2030. To guarantee that all sectors of the economy contribute to these goals, RED III also includes targets specific to sectors, namely buildings, transport, and industry, where the uptake of renewable energy has been comparably slower. In the building sector, for instance, the objective is to attain a renewable share of final energy consumption amounting to 49% in 2030. RED III provides further specifications regarding the heating and cooling of buildings. It establishes a minimum annual average binding increase of 0.8 percentage points of renewables between 2021 and 2025, and of 1.1 percentage points between 2026 and 2030. For the transport sector, RED III specifies two options: Member states can choose either to increase the proportion of renewable energy utilized in their transport sector's final energy consumption to a minimum of 29%, or to reduce this sector's greenhouse gas emissions by 14.5% by 2030 compared to the emissions that would have been created using only fossil fuels. Furthermore, RED III includes a sub-target especially relevant for biomethane and SNG: At least 5.5% of the renewable energy supplied to the transport sector needs to come from advanced biofuels and from renewable fuels of non-biological origin (RFNBO) by 2030. RED III also delineates the precise sustainability criteria that biomethane/Bio-CNG and SNG must satisfy in order to be classified as advanced biofuel and RFNBO, respectively (European Parliament and Council of the European Union, 2023). In addition to RED III, the Fit for 55 package encompasses further regulations, including the *ReFuelEU Aviation* and the *FuelEU Maritime*, which facilitate the advancement of biomethane and SNG further (European Biogas Association, 2024). In this regard, the *RePowerEU Plan*, introduced in 2022 as response to the war in Ukraine and the subsequent energy crisis, represents another significant acceleration in efforts to reduce Europe's dependence on fossil fuels, especially those imported from Russia (Dupont et al., 2024; Tosun, 2023a). This is to be achieved by increasing domestic renewable energy production. A key objective of the RePowerEU initiative is to increase the production of biomethane, with the target of achieving an annual output of 35 billion cubic meters (m^3) in the EU by 2030. This plan not only enhances the role of renewable gases but also seeks to expand the infrastructure for biomethane production and transport, thereby ensuring a more integrated position within the European energy grid (European Commission, 2022). The most recent EU-level approach is the *EU hydrogen and gas decarbonization package*, which was adopted in 2024 and consists of Directive (EU) 2024/1788 (European Parliament and Council of the European Union, 2024a) and Regulation (EU) 2024/1789 (European Parliament and Council of the European Union, 2024b). The primary purpose of this decarbonization initiative is to facilitate the transition to a low-carbon gas system and to advance the utilization of hydrogen as a pivotal energy carrier, thereby enabling the EU to attain its climate neutrality objectives by 2050. It establishes competitive hydrogen markets, promotes the use of renewable gases like biomethane, and sets guidelines for infrastructure development, cross-border trade, and consumer protection (Tanase & Anchustegui, 2023). As one example, the latter ensures that consumers are adequately informed about sustainable alternatives for their residential heating tariffs and have access to suitable financing options and subsidies (European Parliament and Council of the European Union, 2024a).

This compilation illustrates that renewable gases have been the subject of political debate at the European level and that this policymaking is constantly evolving, and has been especially in recent years (Dupont et al., 2024). Additionally, there are further policies at the national level in Germany: Central for/in Germany is the *Renewable Energy Sources Act* (Erneuerbare-Energien-Gesetz, EEG). The EEG is a pivotal piece of legislation that has been providing financial incentives for the generation of renewable energy, including biogas and biomethane, since 2000. These incentives are designed to encourage the production of biomethane through feed-in tariffs or auction-based remuneration models. The 2009 and the 2012 EEGs, which established separate funding for biomethane, led to a notable increase in the expansion of plants. However, this was abruptly terminated with the (controversial, see Bahnsen et al. (2016)) abolition of support mechanisms in the 2014 EEG. With the ratification of RED II in 2018 and its implementation in national law, amendments to the EEG, as well as changes in the fuel sector, have led to a significant increase in demand for biomethane since 2020. This has also led to a (modest) resurgence of new plant projects (Reinholz & Völler, 2023). Moreover, the EEG is increasingly aligned with the national strategy to incorporate Power-to-Gas technologies that help to balance fluctuations in renewable power generation (Bundesamt für Justiz, 2024). Another central legislation in Germany is the *Building Energy Act* (Gebäudenergiegesetz, GEG), especially following its latest (controversially debated, see Kern et al. (2023)) amendment in 2024. This initiative seeks to promote the utilization of renewable energies in heating and cooling systems, with a substantial proportion derived from renewable gases such as biomethane. Starting from 2024, newly installed residential heating systems should be powered by at least 65% renewable energies. There are transitional periods (e.g., the possibility to install a heating system that runs on less than 65% renewables for five years) and several exemptions (e.g., depending on municipal heat planning) as well as no immediate replacement obligation for existing heating systems. Nevertheless, a definitive deadline has been set: from 2045, the operation of heating systems with fossil natural gas or heating oil will no longer be permitted. The use of renewable gases is seen as a crucial element in the decarbonization of heating, particularly in buildings where electrification is either not yet feasible or not yet cost-effective (Bundesamt für Justiz, 2023). This is expected to drive the demand for renewable gases significantly in the coming years (Reinholz & Völler, 2023). This approach to greening residential heating can also be found on the state level: In the South-Western state of Baden-Wuerttemberg, the 2015 *Renewable Heat Act* (Erneuerbare Wärme Gesetz, EWärmeG) requires buildings to cover a portion of their heating needs with renewable energy when they replace or update their heating systems in existing buildings. This law is deliberately designed to be technology-neutral for meeting the required 15% share of renewables. This means that various renewable technologies for utilizing heat can be implemented or combined. Alternatively, substitute measures are possible. Biomethane and renewable gases can fulfill these requirements, though biomethane usage is capped at 10%; tariffs with more biomethane than this cannot be accounted (Ministerium für Umwelt, Klima und & Energiewirtschaft Baden-

Württemberg, 2024). The EWärmeG is therefore stricter than the GEG, which states that in regions without municipal heat planning, heating systems that can also use 100% fossil fuels may be installed during an interim period. This does not apply in Baden-Württemberg, where 15% renewable energies are still mandatory when renovating heating systems.

This compilation provides an overview of the most relevant policies and legislation on renewable gases. It elucidates how multilevel governance shapes renewable gas markets. We can conclude that the issue occupies a position of high relevance on the political agenda, especially in the form of sector-specific targets. However, this does not translate proportionally to market uptake and salience: In 2022, the European production of renewable gases represented just 6% of the EU´s natural gas consumption, the largest share of which was in the form of biogas to produce electricity (European Biogas Association, 2023). For consumers, renewable gases are and will remain scarce for the time being.

1.3 Theoretical rationale

The theoretical considerations guiding this dissertation can be split into three perspectives: From a macro-perspective, replacing fossil natural gas with its renewable substitutes is framed within the transition literature of socio-technical (energy) systems; the literature and frameworks on energy policies (de-)regulating energy and gas markets form the meso-level, while individual decision-making and consumer preferences constitute the micro-level.

The transition(s) of energy systems involve complex socio-technical changes that go beyond mere technological developments and advances. "Energy systems are deeply enmeshed in broad patterns of social, economic, and political life and organization, and significant changes to energy systems increasingly are accompanied by social, economic, and political shifts" (Miller et al., 2015, p. 30). In this regard, scholars like Geels have advanced the discourse on socio-technical transitions significantly (Nesari et al., 2022): His work on the Multi-Level Perspective has been influential in understanding long-term shifts from one socio-technical system to another (Geels, 2002, 2005; Geels & Schot, 2007). Typically, multilevel approaches in policy science refer to analyses of governance structures in multilevel (political) systems such as the EU and its member states, where authority is diffused on multiple levels of decision-making (Hooghe & Marks, 2001; Kohler-Koch & Rittberger, 2006; Tosun et al., 2019; Tosun & Hartung, 2018). Geels, however, uses different levels as analytic lenses to examine transitions from an alignment perspective of processes at niche, regime, and landscape levels. Some scholars have criticized this approach for displaying a bias toward bottom-up change models or for lacking agency, for instance (Geels, 2011). In particular, Smith et al. (2005) argue that the role of actors and their choices – that is, the role of governments, the development of business strategies or individual user choices – are not sufficiently taken into account. Foxon (2011, p. 2260) adds "[…] that the transition approach gives relatively little emphasis to economic factors, such as investment and relative prices, in influencing socio-technical change. Hence, we suggest that the socio-technical transition approach could be usefully complemented by other strands of research with an explicit evolutionary framing”. This suggestion concurs with the view of Shove and Walker (2007), who emphasize the need for holistic approaches that take into account the interconnected nature of socio-technical systems and stress the importance of understanding the coevolution of social and technical elements within these systems. The theoretical considerations on the macro-level guiding this dissertation are therefore based on Foxon´s “Coevolutionary framework for analysing a transition to a sustainable low carbon economy”, which combines insights from socio-technical transition studies and coevolutionary approaches (Foxon, 2011). It uses five systems, each evolving dynamically and influencing/influenced by the other systems through causal interactions. These systems are: *Ecosystems, Institutions, User practices, Business strategies, and Technologies*. Foxon´s framework has been used to guide several studies and analyses, including Brown and Martiskainens´ (2024) study of the development of heating, cooling and ventilation regimes in three European countries, an analysis of socio-technical barriers to domestic hydrogen futures (Gordon et al., 2023); and the development of pathways for energy storage technologies (Taylor et al., 2013). These studies profit from their examination of the dynamic interplay between interconnected systems that are mutually influential (Foxon, 2013).

In Table 1-1, I provide the definition of each system based on Foxon (2011) and adapted to the specific context of this dissertation. While ecosystems and technologies are immanent components of this dissertation and the five articles underpinning it, each article additionally analyzes at least one of the other systems in Foxon’s framework. With its analysis of biomethane offerings and policies, article 1 focuses on business strategies and institutions. Article 2 investigates user practices and business strategies by combining consumers´ and experts´ views on heating markets. Article 4 does too, since it jointly examines consumer willingness-to-pay and the production costs for renewable gases in the residential sector. Articles 3 and 5 explicitly address user practices, analyzing preferences for renewable gases in different markets. As gas, heating and fuel markets are highly regulated and different policy instruments are therefore highly relevant (Aguirre & Ibikunle, 2014; Banja et al., 2019; Menges & Beyer, 2017; Mukherjee, 2021), all articles discuss the corresponding regulatory framework, that is, the respective institutional setting.

Table 1-1: Systems and their definitions from the coevolutionary framework

System	Definition
Institutions	Ways of structuring human interactions, i.e., “the rules of the game”. These include regulatory frameworks on different levels (European and national) for different foci, e.g., CO_2 emission targets for specific sectors (like residential heating) or the (financial) promotion of specific technologies.
User practices	Routinized, culturally embedded patterns of behavior related to fulfilling human needs and desires, i.e., fulfilling the need for heated homes or mobility within existing systems while taking into account other individual desires, e.g., for climate and environmental protection.
Business strategies	Means and processes by which enterprises organize their activities to achieve their socio-economic objectives, i.e., the procurement and sale of different gas products within different markets (e.g., residential heating or mobility) while ensuring financial viability and/or profit. This can also include various other steps along the value chain, e.g., operating own production facilities or (cross-)selling other products such as electricity.
Ecosystems	Systems of natural flows and interactions that maintain and enhance living systems, i.e., switching from natural gas, which relies on the fossilized remains of ancient ecosystems, to low-carbon renewable gas alternatives, which rely on current ecosystems for biomass or capture current energy flows (solar radiation), all of which have direct and indirect impacts on natural ecosystems.
Technologies	Methods and designs for transforming matter, energy and information from one state to another in pursuit of a specific goal, i.e., converting energy crops or manure into biogas, which is then upgraded to biomethane, or using electrolysis to store excess electricity from renewable sources as hydrogen, which is then upgraded to SNG and slated for use as a direct natural gas substitute.

Given this relevance of the regulatory framework, I shall provide a concise sketch of the literature on policies that regulate (renewable) energies and gas markets. Following Mukherjee (2021), Barnea et al. (2022) and Qudrat-Ullah (2022), we can distinguish three approaches to supporting renewable energy capacities: regulatory, market-oriented, and funding. The aforementioned authors focused on renewable electricity, yet this differentiation can also be found for renewable gases. *Regulatory instruments*, such as feed-in tariffs, feed-in premiums, net metering or requirements for consumers to reach specified renewable targets or use specific technologies, seek to expand renewable energy and provide long-term stability by imposing strict requirements, often limiting market competition. In contrast, *market-based instruments*, such as renewable energy quotas and tradable certificates, rely on free market dynamics (i.e., targets are set, but how they are achieved is open to competition) and penalties for non-compliance to encourage the expansion of renewable energy. *Public funding instruments*, including tax breaks and direct investments, provide financial support to renewable energy suppliers. The transition between the individual instruments is not always straightforward. Take, for instance, the EU Emissions Trading System, which affects the price of various energy sources but is fundamentally a strict limit on emissions. The effectiveness of these instruments in increasing renewable energy is debatable. Barnea et al. (2022) conclude that funding instruments have limited significance, but they also find evidence supporting the positive impact of both regulatory and market-based instruments. The effects of these policies can be further differentiated: Regulatory instruments appear to be crucial in encouraging the initial market uptake of renewable technologies, while market-based instruments are effective in sustaining investment once these technologies are mature and well established in the market (Barnea et al., 2022; Marques et al., 2019). In this regard, article 1 provides an explicit analysis of different policies. The other articles discuss the relevant European and national policies and frameworks as well as their implications.

On a micro-level, individual decision-making and consumer preferences are highly relevant for this dissertation. This relevance does not come without substantial (normative) criticism. A key question, particularly from the perspective of ecological economics, is whether decisions over climate protection and the interests of future generations should be made according to the preferences of the present generation. Critics argue that individual preferences may be unstable or based on incomplete or incorrect information. On the other hand, from a political economy perspective and also in line with Foxon´s coevolutionary framework (Foxon, 2011), political decision-making and consumer preferences, that is, institutions and user practices, should inform each other in order to achieve effective and efficient policy design. In light of this, I shall briefly define preferences in the context of renewable gases. In economic theory especially, preferences are often defined as "[…] a decider's attitudes towards consequences or towards choice alternatives" (Eisenführ & Weber (2003, p. 31), translated after Menges & Beyer (2017, p. 56)). This suggests that preferences are linked to particular options or decisions, whereas attitudes (e.g., toward climate protection) are more general. Attitudes are regarded as underlying tendencies that affect individual behavior and are considered when measuring preferences. It is therefore paramount to underline a characteristic of renewable energies that clearly sets them apart from other products: They have an impact not only on the interests and needs of individual consumers, but also on the needs and interests of society as a whole (Menges & Beyer, 2017). Put differently, the development of renewable energies as a means of combating climate change can be considered as a public good (Goeschl et al., 2020; Weimann et al., 2022). This has the downside of potentially resulting in a free-rider problem and crowding-out effects (i.e., public investments in renewables are considered as substitutes for individual and voluntary contributions) (Menges & Beyer, 2017). Taking this further, it is possible to identify two streams of sustainable consumption research. One is a rather market-optimist perspective emphasizing the role of responsible individual action to achieve changes in consumption. This approach is contested by a rather market skeptic view, arguing against a "privatization of sustainability" (Grunwald, 2010). The main argument here is that sustainability is a task for political systems, and the task of individuals is to advocate sustainability politically. While both perspectives are polarized, the shared responsibility model deems both individual consumption decisions and political frameworks as central for achieving sustainability goals and can therefore be considered as a compromise (Menges & Beyer, 2017). Unsurprisingly, the field of renewable energies also uses numerous models, explanations and frameworks on sustainable consumption: for instance, the Norm Activation Model (NAM) (Schwartz, 1977), Value-Belief-Norm Model (VBNM) (Stern, 2000), the Theory of Planned Behavior (TPB) (Ajzen, 1991) or the idea of a "warm glow of giving" when deciding for renewable energies (Chan & Dinelli, 2020)[1]. Article 2 explicitly discusses different models of sustainable consumption and points out their limitations when explaining decision-making for renewable energies.

Energy transitions are complex processes unfolding across and influenced by multiple systems. This holds true for both renewable electricity and renewable gases. The latter has received far less attention in the academic literature and is the focus of this dissertation. Furthermore, their dynamic character requires appropriate consideration. Foxon´s (2011) coevolutionary framework offers a robust analytical lens by explicitly considering the mutual and dynamic interdependencies between five systems (ecosystems, institutions, user practices, business strategies, and technologies) from a macro-perspective. On a meso-level, national and supranational policies and political frameworks shape renewable gas markets significantly, both directly and indirectly. On a micro-level, individual decision-making and consumer preferences play a significant role for the market development of renewable gases as well as for formulating effective policies. The aim of this dissertation is to bring together and analyze these three perspectives.

1.4 Methodological approach

To realize this objective, this dissertation employs a mixed-method approach, using qualitative and quantitative methods in the articles. Given the limited existing research, the overall approach was exploratory rather than confirmatory and used primary data. The modus operandi of gaining successive new insights is reflected in the selected methods: Articles 1 and 2 use a rather open, qualitative approach, while articles 3-5 build on those insights and use quantitative analyses.

The first article, which examined the relationship between policy frameworks and biomethane tariff offerings for residential heating across four countries, was conducted using two separate approaches that were later combined. The policy analysis employed a systematic screening process to identify pertinent policies at the national and EU levels through a range of sources, including EU and IEA policy databases, government ministries, industry associations, and scientific literature. These policies were then subjected to a content analysis and categorized according to various criteria, such as policy type or targeted markets. The product analysis, on the other hand, was conducted through an online content analysis (Krippendorff, 2019), an approach often used in (renewable)

[1] For an overview, please see Jackson's review on consumer behavior theories and models (Jackson, 2005).

energy research (Herbes et al., 2020; Kratschmann & Dütschke, 2021; Schmid-Petri & Elschner, 2024). I developed a comprehensive product attribute morphology, 364 biomethane offerings were coded accordingly. To identify providers, I consulted national regulatory agencies, a national industry association, and an established trade journal. The results were then cross-checked using online consumer tariff comparison tools. The analyzed countries (Germany, Switzerland, the United Kingdom, and Austria) were selected because of their established biomethane markets and their direct or indirect relation to EU policymaking, which allowed for international comparison. Subsequently, the tariffs were juxtaposed with the pertinent national policy frameworks, focusing particularly on the impact of policy support, regulations, and incentives on the product strategies of providers. The qualitative approach was selected because of its capacity to facilitate a comprehensive and systematic examination of policy documents and market strategies, thereby enabling to capture the subtle effects of policy instruments on the conduct of market actors.

The second article also used a qualitative approach, again built on two sources. The first is an interview study on 22 private heating consumers conducted between April and July 2020. This approach is then validated through expert interviews and focus groups with a total of 31 renewable gas industry experts in July 2020. Qualitive approaches like this one are especially suitable for new and emerging technologies as they allow for probing into specific areas while giving respondents the freedom to express their personal concerns and opinions. They also enable interaction and clarifications, making it easier to avoid pseudo-opinions, which can occur given previously identified knowledge gaps (Jones et al., 2017; Malone et al., 2010; Thomas et al., 2023). Accordingly, qualitative approaches have been widely used for assessing emerging (renewable) technologies (Herbes et al., 2018b; Jones et al., 2017; Ricci et al., 2008; Thomas et al., 2023). The objective of the semi-structured interviews and focus groups was to identify the factors that influence consumer acceptance or rejection of renewable gases, taking into account their familiarity with the different technologies, environmental concerns, and cost considerations. I analyzed the data using a combination of qualitative content analysis (Kuckartz, 2018; Mayring, 2015) and Grounded Theory (Corbin & Strauss, 2015). This approach is critical for understanding not only what consumers think but also why they hold certain attitudes. The results from this qualitative study were used to design the experiments in articles 3-5.

Articles 3 and 5 employed a comparable methodological approach. Each one utilized online surveys with two Discrete-Choice Experiments (DCE) at their core. Article 3 addresses the topic of renewable gases in the residential heating market, while article 5 focuses on the private mobility sector. DCEs are powerful tools for measuring stated preferences and have been widely used in research on renewable energy, mobility and beyond (for an overview, see Haghani et al. (2021) and the literature review in articles 3 and 5). DCEs require decomposing the research subject into different attributes and their levels. To identify those, I used interview material and literature reviews. Respondents (512 for the heating market, 573 for the mobility market) had to decide between different combinations of those attribute levels on multiple occasions. Using a Hierarchical Bayes (HB) multinomial logit (MNL) model, these trade-offs can be quantified (Hein et al., 2020; Louviere et al., 2010; Orme, 2010; Rossi, 2014). This allows for calculating the relative importance of each attribute level and the overall utility of different combinations of different features. As previous research has shown, costs are highly relevant in decision-making for energy products. Accordingly, the price attributes were developed with the objective of reflecting usual and relatable pricing. In the mobility market, Bio-CNG and SNG prices were transformed into equivalent prices for one liter of (Super) gasoline; for the heating market, I calculated an individual yearly price for every respondent that reflected housing parameters like living area or the refurbishment status of the building. Different price levels were calculated using relative increases that were added to the calculated prices. Respondents were recruited in May and June 2021 via Kantar Profile Networks, which provide access to a representative sample of Germany. Knowledge gaps and pseudo-opinions were still an issue in the online setting. To ensure validity, explanatory videos were produced for both markets and incorporated into the surveys (see HfWU (2021a) for the mobility market and HfWU (2021b) for the heating market video). Participants were required to view these videos before proceeding with the DCEs. In the context of this dissertation, the field of application of well-established DCEs was extended to the area of renewable gases. This is a suitable area of application thanks to its parallels with the well-studied electricity market, even if it has not yet been examined in the literature.

The fourth article builds on the data I also used in the third article. While the latter provides a more general overview of preference differences, the focus of this article was SNG and consumers´ WTP for it in the residential heating market. Determining these involves estimating price sensitivities through price-response functions. This builds on previously identified part-worth utilities (Levy et al., 2004; Wang et al., 2007). WTPs are calculated as the maximum prices which consumers are (ceteris paribus) willing to accept for a specific share of SNG in their product over the reference product, a 100% natural gas tariff. The analysis did not stop here: As argued for by Bai et al. (2023) and Kim et al. (2020), WTP studies should be extended and combine WTPs with production costs. I realized this by identifying the most recent data on SNG production costs for Germany (Schröer et al., 2022), adding typical further cost components for the residential heating market (e.g., grid fees or taxes), and calculating different scenarios to account for the volatile market dynamics following the war in Ukraine as well as for different technologies. This enabled a direct comparison of price sensitivities, WTPs and production costs, closing a relevant gap in the literature on synthetic fuels and the residential heating market.

Selecting Germany as the main focus country for this dissertation was predetermined by the (BGA-PtG)² research project. The data collection for all five articles besides the first were part of the project. Germany serves as an insightful case for these analyses, being among the most "natural gas-hungry" countries in Europe seeking to overcome (import) dependencies and find more sustainable alternatives. It also has a mature biogas market that is currently in transition due to changes in policy frameworks and expiring feed-in tariffs, while renewable gases (especially biomethane) have gained a certain relevance that is expected to increase significantly in the near future. The two markets analyzed, namely residential heating and mobility, are expected to fuel this increase and are the only markets for renewable gases where consumers can act according to their preferences (in contrast to, for example, using renewable gases as raw material in industrial production). Furthermore, residential heating and mobility are markets where policy interventions, like the introduction of E10 (petrol blended with 10% ethanol) or the GEG, have resulted in significant consumer aversion and resistant behavior.

1.5 Empirical findings

Having elaborated on the conceptional, theoretical and methodological background, this section summarizes and compares the empirical findings of the five articles in this dissertation.

1.5.1 Policy frameworks and voluntary markets for biomethane – How do different policies influence providers' product strategies?

The first article provides an in-depth analysis of how biomethane markets are shaped by different policies in the UK, Germany, Austria, and Switzerland. It focuses on how these policies affect the strategic approaches of suppliers, particularly in the underdeveloped heating market for biomethane.

The first central insight is that current policies in all four countries favor the use of biomethane in electricity generation and transport over its application in residential heating, which remains largely unregulated. The closest alignment between the four countries can be found in the mobility sector, where a market-based policy instrument, namely RED II (now III), sets quotas for either a minimum share of biofuels or for emission reductions. Biogas use for heating is supported in all four countries through a mix of public funding instruments (like investment subsidies and loans) and especially regulatory measures (like feed-in tariffs and premiums).

Focusing on Germany and the supply side of biogas/biomethane, we find that the regulatory instrument of the EEG especially and its feed-in tariffs/tendering system have resulted in a clear focus on electricity generation. Put differently, there is no need for energy companies to target voluntary (heating) markets. On the other hand, this means market capacities and opportunities that go beyond established business models (like, e.g., feed-in tariffs) might have been underestimated or missed. On the demand side, two central market-based instruments targeting heating consumers were identified: The federal Renewable Heat for Warming Act (Erneuerbare Energien Wärme Gesetz) mandated the use of renewable energies in new buildings, with biomethane being one of the options. If a gas-based heating system was installed, at least 30% had to come from biomethane. It was replaced by the GEG on November 1, 2020, which requires 65% biomethane for new buildings in its latest version (see central concepts). The second relevant market-based instrument is the aforementioned EWärmeG in the federal state of Baden-Wuerttemberg, which is still in place. It requires a minimum renewable share of 15% in the case of a building or heating system refurbishment, 10 percent points (i.e., two thirds) of this requirement can be fulfilled through heating tariffs containing 10% biomethane. The product analysis for Germany revealed two important insights: First, with 65% of all tariffs under review, the market for biomethane is dominated by tariffs containing 10% biomethane (100% and 30% biomethane shares follow with equal yet much lower frequencies) and therefore by the minimum share required by (federal) law. This shows how market-based instruments (indirectly) influence heating markets. Second, the transparency of providers over attributes relevant for consumer decision-making is limited. This is particularly the case for geographic origin as well as for the feedstock used to produce biomethane: For more than two thirds of the tariffs under review, the origin was not disclosed. In addition, more than half of the tariffs had no information on the feedstock. Accordingly, consumers often cannot find the relevant information for informed decision-making, which might make them less likely to choose biomethane. Furthermore, the options remain limited, especially in comparison to renewable electricity, as only 8% of gas providers offered a biomethane tariff. There still seems to be some market dynamic: In a more recent study, Schmid-Petri & Elschner (2024) found that 16% of the municipal utilities in Germany offer gas at least partly based on renewables.

In conclusion, this article demonstrates that policy instruments were inadequate or even counterproductive in driving meaningful change in the heating market, particularly with regard to biomethane market uptake.

1.5.2 Invisible, intangible, irrelevant, yet inevitable? Qualitative insights into consumer perceptions of heating tariffs and drop-in renewable gases in the German domestic heating market

The second article switches perspectives and delves into consumer attitudes toward heating tariffs and renewable gases. First, I analyze the decision-making context. In line with the insufficient provision of information identified in the first article, consumers often perceive tariffs and their structures as complicated and confusing, further complicating decision-making. Furthermore, the article reveals that decisions over heating tariffs are low-involvement, that is, they are not primarily driven by the product itself but by different aspects like the provider, price considerations or the drive for upholding the status-quo (i.e., consumers are reluctant to realizing changes like finding a new provider). It is noteworthy that consumers motivated by climate protection who have already selected a renewable gas product demonstrate this low level of involvement as well, as they are often uncertain about the specifics of their tariff. This article is the first to test the claim of low involvement empirically in the heating market.

In a second step, the article sheds light on consumer attitudes, preferences and reservations toward renewable gases. It reveals a dichotomy: SNG and PtG as the newer and less well-known technologies are perceived as neutral, which aligns with research related to hydrogen (Gordon et al., 2022). Consumer perceived their capability of storing surplus electricity and using it in heating positively. However, they highlighted the importance of utilizing surplus electricity, and the potential for efficiency losses was acknowledged as a key concern. The perception of biomethane, conversely, was far more complex and nuanced, as consumers show a much higher degree of familiarity with the underlying technology. However, this does not necessarily translate into knowledge. In general, consumers hold favorable views on the transformation of biomass and especially waste materials into energy that can be used in existing infrastructure, particularly since this also mitigates climate change. However, this attitude reverses vis-à-vis the prospect of biomethane production on an industrial scale (see also Bourdin & Delcayre (2024)). Consumers raised concerns over "food vs. fuel", albeit in a rather diffuse and relativizing manner, which indicates changes in public perception. Importantly, and in concurrence with the considerations on low involvement, costs play an important role in the evaluation of renewable gases.

Validating these insights with industry experts, confirmed the result of the first article with regard to market size: The voluntary heating market for renewable gases is considered small. In addition, consumers are (accurately) perceived as cost-driven and used to low prices, especially in the renewable electricity market. Furthermore, experts highlighted confusion among consumers, who cannot differentiate "real" renewable gas products from eco-gas products based on compensations for emissions. The real advantage of SNG over biomethane was seen in the avoidance of the "food vs. fuel" debate. Interestingly, two of the solutions identified by the experts to accelerate market development are policy interventions: An increased price for CO_2 emissions from fossil gas (i.e., a market-based instrument) or a legal requirement to use renewable gas in heating (i.e., a regulatory instrument).

This article closes with a critical discussion and assessment of theories of sustainable consumption and their limitations in explaining consumer behavior with regard to renewable gases. Furthermore, it takes up and discusses the idea raised by the experts of increasing CO_2 prices. In summary, this article closes a relevant gap in the literature, for there was a dearth of research on renewable gases as an option for greening residential heating as well as on general decision-making over gas tariffs. The open, semi-structured approach enabled me to acquire initial insights into this field and to prepare the experiment used to gather the data for articles 3 and 4.

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

Building on the interviews conducted in article 3, this article goes into greater depth regarding consumer preferences for renewable gases in the heating market. The interviews (complemented with a literature review) informed the development of a DCE and its five attributes: gas mix (i.e., the share of biomethane and SNG in the tariff), labels (including a fake label and combinations of different labels), proximity of the production site to the consumer, supplier type, biomethane feedstock, and yearly price.

The larger representative sample (n = 512) confirms the initial insights from the interview study: Biomethane is still widely unknown, and opting for a biomethane heating tariff is mostly motivated by legal obligations. Regarding consumer knowledge on the functionality of the underlying technologies (i.e., biogas and PtG plants), we find knowledge gaps for both, though the one for PtG is much more pronounced.

It is notable that, in contrast to what the interviews suggest, decision-making is not only dominated by price considerations. The most significant factor influencing these decisions is the gas mix, with price considerations ranking second. Interestingly, Plum et al. (2019) observed a comparable trend among Swiss electricity customers, which calls into question the notion of price-only dominance. Labels and regionality come (by some distance) in third and fourth position respectively. In comparison to the other decision-making criteria, supplier type and regionality are relatively unimportant. Examining the attribute levels in greater detail, we find (surprisingly) that consumers favor tariffs with biomethane shares. SNG is only preferred for smaller shares in the tariff, which can be partially attributed to the price design of the DCE: Instead of using similar prices across all tested renewable gases, prices reflected actual production costs and shares in the product. This mimics the real market situation, where SNG is more expensive than biomethane and higher shares of renewables in the product also increase the price. By no surprise, lower prices are favored over higher prices. The results for labels reflect the previously identified knowledge gaps and insecurity among respondents, as we found a “the-more-the-merrier” effect at play in consumer decision-making. The evaluation of a tariff improves when a greater number of labels is shown, indicating the need for trust signals in the market. It is important to note that this need for trust can be easily manipulated. In addition to the two established labels, we designed and introduced a fake label into the DCE, which outperformed the two existing labels. The results on biomethane feedstock were puzzling: In contrast to existing research, consumers favor energy crops over waste (though only slightly, especially when compared to the other attributes). We therefore cross-checked this with other variables in the dataset and found that the formerly critical evaluation of energy crops as well as the general evaluation of biogas have turned much more positive.

The identification of latent classes from the DCE revealed a high degree of heterogeneity in the data; this approach was therefore excluded from further analysis. It is important to note that this does not interfere with the overall model performance, as the applied HB MNL model captures multimodal preference heterogeneity sufficiently (Goeken et al., 2024). I subsequently segmented the sample according to pre-defined variables. Interestingly, segmenting by housing parameters and by educational levels did not result in significant preference differences. Instead, knowledge (on biomethane) and experiences from similar decision-making situations (i.e., having a renewable electricity tariff) did. In fact, we found that consumers with higher knowledge and a renewable electricity tariff assign more importance to the gas mix and less to the price, as they accept higher prices and are more open to higher shares of renewables in the tariff.

Given the identified knowledge gaps and confusion among consumers, this article emphasizes the importance of raising awareness of and increasing knowledge on renewable gases and labels. This is particularly relevant in light of the first article's findings that tariff offerings are often (too) vague with regard to consumer preferences. The most significant insight is that the previously negative perception of biogas and biomass appears to have diminished, particularly when it comes to selecting a heating tariff. This certainly can and should inform policymaking as well as marketing strategies.

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

The fourth article analyzes prices and consumer WTP in the heating market in more detail. It focuses on SNG to inform future decision-making, as the relevance of this fuel type is expected to increase.

To operationalize the central price attribute, I calculated the individual yearly prices for all respondents. This solved an issue of many DCEs and other pricing studies, namely that using a per unit price (e.g., kWh) suffers from deviations from the actual payment procedure, which is usually settled through monthly installments and later through an annual bill. Furthermore, given the identified knowledge gaps and low involvement, consumers cannot be expected to have a realistic idea of unit prices. Using an average aggregate price (like yearly costs) for all participants is inadequate for capturing highly relevant individual housing parameters like construction year, living area or the refurbishment status. The DCE conducted for this article therefore used a two-step approach. Respondents were first asked about their individual heating parameters. This information was then used to calculate an individual yearly price, which was subsequently integrated into the DCE with identical relative price increases (per cent) for different products. Participants, however, only saw “their” individual yearly price and increases thereof. This approach ensured comparability between cases while guaranteeing realistic price estimates: With the average calculated yearly fuel costs for heating and hot water standing at €846, this estimate is close to the 2021 costs of €820 obtained from official data (Heizspiegel, 2022).

The results reveal an insight that was already apparent in the third article: In a market simulation based on 0% price increases, I identified clear preferences for biomethane over SNG. More than 2/3 of the respondents would opt for a tariff containing biomethane, while only 23% would opt for a SNG tariff. Surprisingly, 5% would stick with a natural gas product even though the renewable share does not come with extra costs. Looking at the WTP for SNG reveals a surprisingly high initial WTP for only a small share of SNG: 40% relative WTP surplus for only a 5% share of SNG in the tariff. Put differently, respondents value this new renewable gas product highly. However, WTP and shares of SNG do not increase proportionally: The average WTP surplus for a 100% SNG tariff stands at approximately 69%. This leads me to conclude that consumers are surprisingly willing to bear significant extra costs, though probably not enough to cover significantly higher production costs for products with high SNG shares.

I compare the two in the last analytic step of the article. In both the best-case (considered optimistic with regard to electricity and natural gas prices) and the normal-case (considered realistic following the war in Ukraine) scenarios, the identified WTPs only cover the retail prices of products with small shares (5% and 10%) of SNG. WTPs do not even come close to covering higher SNG shares. Prices would have to come down significantly to open the market for those higher shares. This insight led me to analyze further (market-based and regulatory) financing mechanisms. In line with Tröndle et al. (2023), I find consumers tend to reject measures that directly add costs to their bill (like levies on fuels) and prefer financing via the general governmental budget or direct financing via the retail price.

In view of the identified preferences for the more established biomethane, which consumers now tend to perceive less negatively, and in combination with insufficient WTPs for higher shares of SNG (which would be necessary for a significant contribution to greening residential heating), this paper concludes that the potential benefits of channeling expensive and still rare SNG into the heating market should be carefully weighed against the potential drawbacks.

1.5.5 Renewable methane fueling the sustainability transition in private transportation: Identifying consumer preferences through a Discrete-Choice Experiment

The last paper of this dissertation switches markets and analyzes the small yet relevant market for renewable gases sold in the private mobility sector, namely CNG, Bio-CNG and SNG. Market-based policy instruments have led to almost no fossil natural gas being sold in this market. In particular, RED II, following its implementation through national law, has made Bio-CNG an attractive option for fulfilling emissions reduction quotas as it comes with drastic penalties for failed quota requirements. Selling waste-based biomethane as Bio-CNG as well as GHG quotas to fuel distributors offer lucrative revenue streams for biomethane plant operators. This means that CNG drivers have no real choice when refueling their cars, which potentially neglects their preferences. This paper takes this issue into account and can inform the decision-making in other fuel segments as well, especially in light of the ongoing debate over synthetic fuels.

The methodological and analytical approach used was similar to the one employed in the third article. Although I drew a new and independent sample for this survey, the results pointed in a similar direction: I found knowledge gaps for both technologies (i.e., biogas and PtG), especially for PtG. However, this difference is less pronounced than in the third article. This further confirms the previously identified knowledge gaps for alternative fuels (Linzenich et al., 2019, 2023). With regard to attribute importance, the gas mix is even more important than in the heating market. Subsequently, price and labels are identified as additional key influencing factors, although their relevance is clearly less significant. Regional production and Bio-CNG feedstock are also less important. Again, unsurprisingly, consumers prefer lower prices. Furthermore, the label effect found in the heating market can be confirmed for the mobility market as well: Consumers prefer products with more labels over less labels and can be "tricked" by a fake label outperforming the established labels. In regard to the comparison between the biomass-based Bio-CNG and the electricity-based SNG, the results of both the 0% prince-increase scenario and the mean utilities indicate a clear preference for Bio-CNG over SNG. This concurs with the third and fourth articles, yet in stark contrast to older research, indicating an aversion toward biomass-based fuels (Linzenich et al., 2019, 2023; Tosun, 2017).

I therefore conclude that the current CNG market reflects consumer preferences well: CNG drivers get what they want – a biomass-based fuel – though the market is not driven by these preferences but by legal requirements. This case study illustrates the potential for a low-involvement market to be steered toward emission reductions through the implementation of policies, without the adverse reactions commonly observed in other contexts, such as the introduction of E10. The admittedly small (and declining) private CNG market seems to be a good demo-site for testing policy measures that could be transferred to other segments.

1.6 Conclusion and the way forward

This dissertation set out to investigate how renewable gases can successfully contribute to an energy transition beyond electricity, especially in the residential heating and private transportation sectors in Germany. Theoretically it builds on the assumption that energy transition(s) take place in different systems which evolve over time and reciprocally influence each other (Foxon, 2011). The five articles of this cumulative dissertation explicitly focused on three systems: institutions, user practices, and business strategies. I analyzed the other two systems – ecosystems and technologies – implicitly by focusing on renewable gases' significantly lower GHG emissions compared to fossil natural gas. This dissertation builds on existing literature on energy policymaking, consumer preferences, and other renewable energy segments. Given the scarce body of literature on renewable gases, especially on the demand side, I have drawn upon relevant and comparable studies, primarily from the field of renewable electricity. Empirically, the articles investigate the influence of different policies on biomethane markets, the attitudes and parameters influencing decision-making for heating tariffs, consumer preferences for renewable gases in residential heating and private transportation, and the (mis)matches between consumer WTP and the production costs of SNG. Overall, this dissertation contributes to a better understanding of how different subsystems influence each other and how they can be aligned to contribute to a successful energy transition beyond electricity.

The first article of this dissertation focuses on different policies on the biogas and biomethane markets in four countries and their influence on biomethane offerings to private consumers in the residential heating market. It contributes to the literature by exploring how regulatory instruments especially have led to only small shares of biomethane in (voluntary) heating markets and how these policies clearly favor electricity generation and transport. Secondly, it shows how market-based instruments indirectly influence providers' renewable gas offerings to consumers in Germany. This illustrates how the regulatory instruments in place to encourage the market uptake of biogas (Barnea et al., 2022; Marques et al., 2019) still hamper voluntary markets, such as the heating market, which is only regulated indirectly by market-based instruments. Lastly, this paper adds to a better understanding of how energy suppliers can reach their consumers by providing them with the relevant information necessary for informed decision-making.

The second article is the first to explicitly analyze decision-making for heating tariffs, a topic that is notably absent in the existing literature. Using semi-structured interviews, it builds on an empirical method well established for new and under-researched topics especially. Its empirical contribution therefore lies not only in analyzing the consumer perspective, but also in validating this perspective with industry experts and their perceptions of consumers. This provides a more holistic combination of demand- and supply-side perspectives. Furthermore, this article contributes to the body of literature on (marketing) renewable energies by empirically testing for residential heating tariffs the oft-made claim that energy products are considered low-involvement products (Friege & Herbes, 2017). As for its theoretical contributions, this article shows that several established theories in the discourse on sustainable consumption cannot fully explain the specific decision-making context for renewable gases, that is, explain sustainability-related consumer decisions while taking into account technology-related, contextual and habitual factors as well as low involvement. Lastly, this article presents preliminary evidence on a shift in the public opinion on biomass-based energy. This challenges the long-held assumption that consumers are inherently opposed to this form of energy production.

The third and fifth articles expand the application field of DCEs to renewable gases in the heating and private mobility markets. DCEs are widely used in energy research, especially for renewable electricity, heating systems and vehicle choice. Expanding these was overdue, which is an important empirical and methodological contribution. Another important contribution is the production of explanatory videos for both markets. These were not only used in the surveys to avoid pseudo-opinions and ensure validity; being publicly available, they were also used to close (empirically proven) gaps in awareness and knowledge among consumers (e.g., by the grant program coordinator of the (BGA-PtG)² project). This in turn is central for informed decision-making. Another empirical contribution from both articles came as a surprise: Biomass-based fuel/tariffs are clearly favored over electricity-based SNG. This has resulted in policies that have created a good alignment of consumer preferences and supply in the mobility market. For the heating market, it challenges the idea of channeling SNG into the market, which is analyzed in more detail in the fourth article.

This fourth article also made important empirical and methodological contributions. Operationalizing the central price attribute took individual heating parameters into account, which enabled realistic decision-making. This is not the case when using other price designs like kWh prices or average prices for all respondents. Furthermore, while there are studies on WTP for renewables in the heating market, albeit not in a European/German context (Kim et al., 2019; Kim et al., 2020), they lack combining WTPs with actual costs. For SNG especially, although research exists on production costs, these are not transferred into actual consumer prices that take into account other price components besides production. This article fills this lacuna and finds significant gaps between WTP and consumer prices for higher (and therefore costlier) shares of SNG, which challenges the idea of SNG being a relevant solution for greening the residential heating market. Moreover, this article again confirms that consumers prefer biomethane over SNG.

This last insight requires further discussion. One potential explanation for the shift in attitudes is habituation over time: As consumers acquire more knowledge on biomass-based energies, they display less aversion to them. We might also see the effect of policy interventions like the maize cap, which controls and reduces the controversially perceived maize (Herbes et al., 2014). Another explanation stems from the studies which highlight this aversion, as they mostly analyze biogas and biomethane as resources for producing “something else”, such as electricity or plastic. Here, I wish to draw on the second article and on consumer perceptions of SNG, which was criticized by interviewees for using electricity to produce “something else” (i.e., SNG) that was linked to efficiency losses. A similar logic could be at play when evaluating the use of biomethane in residential heating and mobility, for consumers might value the direct use of gas in its original form. This certainly calls for further research that considers public perceptions following the Russian invasion of Ukraine in 2022 (Agentur für Erneuerbare Energien, 2022).

All the data used in this dissertation were collected before this invasion and the subsequent political decisions, which widely affected energy markets and energy prices (Liu & Lee, 2024). Since both, markets and prices, have largely stabilized (Adolfsen et al., 2022; Maneejuk et al., 2024); therefore, I assume my findings and policy recommendations still hold true. Where possible (especially with regard to prices and WTP), I used scenarios and different assumptions to reflect the dynamic situation. Even so, I highly recommend future studies to (re-)analyze the market situation of renewable gases, taking into account the new situation in the various energy markets.

As for renewable gases, the private mobility sector definitely represents a specific case, since CNG was and is a niche market with an unclear future (ADAC, 2023). Once a forerunner for SNG (Audi, 2013; Chemie.de, 2023), it is now dominated by Bio-CNG especially because of market-based policy instruments. The heating market, on the other hand, presents a more fruitful field for analysis. As shown, renewable gases currently suffer from only indirect market-based policy instruments; the question therefore arises as to whether the use of these instruments in the heating market came too early for a rather immature market – especially considering there is currently no significant alternative for direct use in existing gas heating systems besides biomethane. This is highly relevant given that gas-based heating is the most common heating system in Germany and that this position has been partially reinforced by the unintended effects of another market-based policy intervention, namely the GEG (BDH, 2024b). This development reinforces the arguments of critics, particularly with regard to infrastructure and behavioral lock-ins, stranded assets and crowding-out effects (Brauers, 2022). In this respect, renewable gases could potentially support these effects in the long-term (Böck, 2024; Herbes et al., 2021) or create new upstream dependencies and problems related to fodder supply for manure-based biomethane (Magnolo et al., 2024). At the same time, they harbor good potential for greening residential heating in the short- to mid-term. The discourse evolving around renewable gases occurs within this context of conflicting interests. Interestingly, and in this context highly salient, large natural gas lobby organizations, like Zukunft Gas, also argue for renewable gases (Zukunft Gas e.V., 2024). However, it is unrealistic that the existing infrastructure can meet the market demand for biomethane (Rilling et al., 2024). Furthermore, the biomethane market in Germany is currently characterized by insecurity and consolidation. In fact, two prominent companies in the biomethane and GHG quota trading sectors, Landwärme and bmp greengas, have been forced to file for insolvency (Solarserver, 2023, 2024). This calls for further research. In particular, the analytic focus of the framework I applied – namely the co-evolutionary approach and the analyzed systems – could inform further analyses.

What are the broader implications and limitations of this, particularly in light of the theoretical rationale that underpins this dissertation? Overall, this dissertation enhances the theoretical understanding of energy transitions by focusing on renewable gases in two underexplored sectors, namely residential heating and private transportation, and how gaps between policies, markets and consumer behavior can be bridged. Foxon´s co-evolutionary framework (Foxon, 2011) was especially helpful in showing how the different systems influence each other and evolve over time. Given the character of energy transitions, this co-evolution is ongoing. The five papers of this dissertation, along with the underlying empirical material, can be regarded as snapshots, or cross-sectional studies, which are unable to fully capture the dynamic in question. This holds especially true for the institutional setting, which has evolved significantly since I conducted the analysis for the first paper (as explained in the overview of the central concepts). Furthermore, I analyzed the different dimensions of the framework separately, with no paper explicitly examining all five dimensions. Further research could span a longer period and combine all systems and their causal influences, for instance, using a discourse analysis. A key area that is undertheorized in the framework and also beyond the analyses presented in the five papers of this dissertation is the role of power and intermediaries, including lobby organizations, (non-governmental) interest groups, and the media. As Tosun (2017) has shown for the mobility sector, intermediaries play a pivotal role in influencing the efficacy of policy measures. Further research could examine the impact of other intermediaries, such as professionals engaged in energy transitions on a daily basis, including heating installers and energy advisors, particularly in the context of recent amendments to the GEG. Explicitly adding this perspective to Foxon´s framework would also help with analyzing the interdependencies and causal influences of different systems.

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2) Policy frameworks and voluntary markets for biomethane – How do different policies influence providers' product strategies?

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Abstract Replacing natural gas with biomethane is an option to help decarbonize residential heating and cooling. But little biomethane is in the voluntary markets for heating. We examined biomethane-based gas tariff offerings in the UK, Germany, Austria and Switzerland, using qualitative content analysis and compared them to the national policy contexts. We find that current policies in all four countries under review clearly prioritize using biomethane for electricity generation and in transport, while leaving the heating market largely unregulated. Nonetheless, we find influence of policies on the heating market. Offerings in Germany show this influence in their biomethane content and underlying feedstock and in Austria regionality seems to be driven by grid charge regulations. If German policy makers want to channel more biomethane into residential heating, they are advised to harmonize competing support schemes for biomethane in electricity generation, transport and heating/cooling, waive mandatory CHP requirements, lower minimum biomethane content and to target existing, not just new, buildings. In the UK, the RHI should include residential buildings and using the Austrian refund system could help to develop biomethane tariffs from regional sources in Switzerland.

2.1 Introduction

Residential heating is responsible for a large part of the total final energy consumption and hence greenhouse gas emissions. In 2017, heating accounted for 48% of the end energy consumption worldwide in the residential sector and for more than 10% of the end energy consumption in all sectors (IEA, 2020). The share of renewables in heating represents only 10% of global heat consumption in 2017, less than half of the share of renewables in electricity consumption. The International Energy Agency (IEA) comments critically: "Greater ambition and stronger policy support are needed to ramp up the use of renewables for heat and to improve energy efficiency in both buildings and industry" (IEA, 2019).

Replacing natural gas with biomethane ("green gas") for heating purposes has strong appeal. In 2017, gas accounted for 43% of the final residential heating demand in the EU (Fleiter et al., 2017); almost none of the gas was green. Green gas can be injected into the public grid and used with existing heating technologies. This is especially important since the lifetime of heating equipment is measured in decades and rates of new construction in developed countries often fall below 1%. While replacing the current heating system stock will occur slowly over decades, renewable gas is available today to help decarbonize the heating of residential buildings.

A growing number of biogas plants upgrade their biogas to grid quality and inject biomethane into the public gas grid. Detailed data for Europe show that 610 biomethane plants were in operation at the end of 2018. Their total production volume for 2018 stood at 22,787 GWh (European Biogas Association, 2020), however that amounts to a mere 0.5% of total natural gas consumption (own calculation based on: European Biogas Association, 2020; Statista, 2020b).

Globally, the IEA estimates biomethane consumption to reach 23 Mtoe in 2025 and 77 Mtoe in 2040 in their *Stated Policy Scenario*. Under the more ambitious *Sustainable Development Scenario*, the consumption in 2040 could reach 206 Mtoe, highlighting the strong impact of energy policies on market developments. D'Adamo et al. (2020) assessed this impact on the industry on the basis of a SWOT analysis. They conclude that "… the adoption of an adequate incentive scheme is of the utmost importance." (D'Adamo et al., 2020, p. 12).

Most governments regard "incentive schemes" or subsidies for renewable energies which are still crucial for the profitability of biogas plants (Cucchiella and D'Adamo, 2016; Eker & van Daalen, 2015) as temporary, aiming to help new technologies become competitive in the market (Herbes et al., 2016). And in fact, governments continue reducing subsidies for the sector (Brémond et al., 2021). An effective policy framework would have companies channeling biomethane into voluntary markets early in the development of the industry, allowing the new market actors to gain experience and build trust in the mind of consumers.

This has happened to a limited extent in some markets, where companies have started to offer biomethane-based gas products (Herbes, 2017). However, the market share of these products is almost negligible: about 0.1% in Germany (Bowe et al., 2018), where more biogas plants operate than anywhere in the EU. Other than Rajendran et al. who posit that "[…] the [biogas] market can survive on its own." (Rajendran et al., 2019, p. 286), the strong reliance of biogas plants in Germany on using biogas to produce electricity which in turn is heavily subsidized, rather proves the contrary: an ongoing dependence on state-led support. While multiple factors explain the low development of the voluntary market for biomethane, the regulatory framework's impact on product offerings is what concerns us here.

Broadly speaking, policy frameworks can impact voluntary green energy markets in four ways. First, and most importantly, they determine whether selling green energy is legal and what requirements energy market actors have to fulfill to participate in the market. Second, they regulate how voluntary markets interact with state-led support schemes or requirements. Are the two completely separate or are volumes sold in voluntary markets eligible to count against green requirements or to receive subsidies on top of sales prices? Third, they set feed-in-tariffs or other support instruments. The support levels set become benchmarks for companies offering green energy in voluntary markets. Generous support schemes may discourage companies from trying to compete with their products in voluntary markets. Feed-in-tariffs set the minimum price a company will ask in a voluntary market, if it is able to access both channels (Herbes et al., 2020).

Finally, where alternative resource utilization paths exist, policy frameworks can influence the competition between paths. Biomethane can be used for heating; but it can also be used as a vehicle fuel or for combined heat and electrical power (CHP) generation. A regulatory framework may favor one path over another, which will impact the development of the respective voluntary markets.

Impacts of policy frameworks on the biomethane market have been well researched for electricity generation (Banja et al., 2019a; JRC - Joint Research Centre, 2017; Torrijos, 2016) and the transport sector (Ahman, 2010; D'Adamo et al., 2019, 2020; Larsson et al., 2016; Lindfors & Ammenberg, 2021; Millinger et al., 2019; Patterson et al., 2011; Rajendran et al., 2019; Smyth et al., 2010). In contrast, no detailed study of the impact of policy frameworks on the heating segment of the biomethane market exists. Both demand and supply side of voluntary biomethane markets are rather under-researched. The few studies that exist on the demand side and the literature on the acceptance of biogas mostly agree that consumers reject energy crops and rather prefer biomethane from waste, regional products, a high share of biomethane in the product and eco-labeled products, using land that could be used for producing food for growing energy crops is a very controversial issue (Forsa, 2012; Herbes et al., 2014, 2018b).

In this study, we aim at analyzing how existing energy policies affect the voluntary markets for biomethane in the heating sector and at formulating policy implications for policy makers wanting to increase the use of biomethane in the heating sector. To our knowledge, we are the first to do so. We find the question of policy influence on voluntary biomethane markets especially pertinent because the heating sector has been subject to little direct policy action in Europe. Our investigation takes the form of an analysis of policies and market offerings in four countries: Germany, the UK, Austria and Switzerland. Germany accounts for a fourth of all plants in Europe and four countries (Germany, the UK, France and Sweden) operate more than half of all plants in this region. However, in both France and Sweden, biomethane is used almost exclusively for transportation, making an analysis of their heating markets of little value.

Germany and the UK, however, represent Europe's two biggest heating markets for biomethane, while the markets in Austria and Switzerland offer characteristics useful for comparison. Aspects that make this country set interesting to study include:

- Biomethane products are firmly established in all four markets but the biogas industry has a different position in each country;
- All markets operate in (Germany, Austria) or close to (UK, Switzerland) the European Union legal framework, facilitating intercountry comparisons;
- All markets remain largely unregulated as regards biomethane use for heating, allowing testing for the emergence of voluntary market products;

- One country (the UK) has implemented mandatory targets for renewable heat use, while the other three legislative frameworks focus on using biomethane and biogas to generate electricity.

Given the four distinct policy environments these countries represent, we can compare different approaches to assess their impact on the voluntary market for biomethane.

Our results contribute to energy policy by offering policy makers insights into the interrelation between regulatory actions and voluntary market development that should help in predicting the impact of future policy decisions.

The rest of the paper is structured as follows. Section 2 explains how we analyzed i) the regulatory frameworks governing the voluntary use of biomethane policies and ii) product offerings in the four markets. Section 3 presents the results of our analysis. Section 4 discusses our findings, while Section 5 presents policy conclusions and recommendations.

2.2 Methods

2.2.1 Policy analysis

As Banja et al. (2019a) and Torrijos (2016) note, market development is highly dependent on the regulatory policy framework that markets operate in. As with other markets for renewable energy sources – see e.g. Gährs & Knoefel (2020) and Inês et al. (2020), the options and barriers for biomethane products as well as their development potential are strongly defined by regulatory frameworks. In the case of the EU member states that we analyze, the European level adds a regulatory frame. Whereas this certainly increases complexity, it also safeguards a minimum harmonization which can serve as the basis for comparison (Scarlat et al., 2018). As a basis for the market analysis, our contribution presents a comparative assessment of the legal frameworks of European markets, with Germany and Austria being covered in the EU framework and Switzerland and the UK operating outside it. Rather than taking interviews (see e.g. Inês et al. (2020)), we performed a staged approach of desk research. The first step consisted in systematic screening of policy databases assembled by the European Union and the International Energy Agency. Especially the latter retrieves information from all its member countries in a standardized manner. This allows to gather basic information, which however has to be corroborated by analyzing national websites of ministries, agencies and associations to make sure that the latest policy updates are covered. In this step, a content analysis of grey literature was performed as well to retrieve information and feedback on the appropriateness of this framework, as perceived by specialists.

Apart from the primary sources (mainly legal texts and government authority websites) our research is informed by the following secondary sources: Information on present policy support schemes for the four countries was retrieved from the Policies and Measures database of the IEA. The "RES Legal" database run by the Joint Research Center (JRC) of the European Commission complemented the insights into existing policy mechanisms. To evaluate critical issues of the legal framework, we used a Scopus screening of scientific literature, supplemented by analysis of grey literature (google scholar, researchgate.net, academia.edu). In addition, Horizon 2020-funded projects and the website content of regulatory authorities helped to identify present framework support conditions for green gas. Since some retrieved information remained patchy and inconclusive, we corroborated existing data by contacting national and European biogas associations as well as experts with the IEA and the JRC.

It has to be noted that many of the existing information remain patchy and in some cases outdates. In turn, our study is the first to juxtapose and compare the regulatory frameworks in the European markets which are the focus of our analysis.

2.2.2 Product analysis

We carried out an online content analysis (Krippendorff, 2019) of green gas products on provider websites in Germany, the UK, Austria and Switzerland. Content analysis has been defined as "[…] a research technique for the objective, systematic, and quantitative description of the manifest content of communication" (Berelson, 1952, p. 18). Both, qualitative and quantitative content analysis are established methods in empirical social science research (Mayring, 2015) and have been used extensively also in energy research. With the rising importance of communication over the internet, online content analysis has gained increasing importance and has been used in numerous contributions on renewable energy before (Borch et al., 2020; Chaiyapa et al., 2018; Herbes et al., 2018a, 2020; Herbes & Ramme, 2014; Kratschmann & Dütschke, 2021; Qu et al., 2009; Zeng, 2018).

We used provider compilations from either national regulatory agencies (Ofgem for the UK, E-Control for Austria), a national industry association (gaz energie for Switzerland) or an established trade journal (Germany). We validated our samples by crosschecking against results from online gas tariff comparison portals, identifying the following number of tariffs for review per country:

- Germany: 127
- Austria: 25
- Switzerland: 188
- The UK: 24.

Based on literature on consumer preferences, we developed a morphology of product attributes that we considered comparable among the four countries (Table 2-1). Most attributes, except for feedstock, are comparable to renewable electricity, for which a recent contribution developed a similar morphology (Herbes et al., 2020) which in turn draws heavily on studies of consumers' willingness-to-pay for green electricity (Oerlemans et al., 2016; Sundt & Rehdanz, 2015). It includes the geographic origin of the production sites, the geographic location of the supplier, eco-labels as well as the supplier type (Herbes et al., 2020). While for green electricity, the production technology, e.g. photovoltaics or wind power plants, is an important attribute, this is not the case for biomethane. But feedstock matters to consumers in voluntary markets, as previous consumer research (Forsa, 2012; Herbes et al., 2018b) and research on the public discourse on biogas (Herbes et al., 2014) as well as on public acceptance of biogas (Dobers, 2019; Schumacher & Schultmann, 2017) has shown.

Table 2-1: Morphology of product and provider attributes

Product-related attributes and values	**Provider-related attributes and values**
Biomethane content: (1–100%)	Geographic location of operation: • Regional • National • International
Biomethane feedstock: • Energy crops • Waste • Mix (energy crops and waste)	Green supplier: • Supplier offers only green/renewable-based products • Supplier does not offer only green/renewable-based products
Geographic origin (location of production site): • Regional • National • International	Commercial orientation: • Purely commercial • Municipal utility • Cooperative
Labels associated to the tariff: • Number • Name(s) • Further information	Additional contributions: • Supplier mentions any further/additional contributions (e.g. donation to an environmental organization/project) • Supplier does not mention any further/additional contributions

From this morphology, we developed a set of coding variables to collect the data (see Appendix A2). For this paper we only analyzed the biomethane content, feedstock and the origin.

Coding was carried out between July 2018 and June 2019 and covered 364 tariffs. However, we made sure to keep the collection period for each country within the same year to avoid inconsistencies due to tariff changes. To eliminate tariff bias in the data, we had to be sure the same conditions prevailed over the entire collection period.

After having been checked for consistency, validity, and completeness, all national data sets were compiled in a single file for further analysis. Further details can be found in the Appendix.

2.3 Results

In section 3.1, we report on our analysis of the regulatory frameworks governing the biomethane markets in German, the UK, Austria and Switzerland. In section 3.2, we present results from our analysis of product offerings in the four countries.

2.3.1 *Policy frameworks*

Measures to support the use of biomethane are largely defined at the national level. The European markets are framed by EU strategies and decisions either directly (in the cases of Austria, Germany and the UK until the end of 2020) or indirectly in terms of policy benchmark (Switzerland and post-EU UK policies). Table 2-2 sums up key EU framework policies existing in this field.

Table 2-2: EU policy framework for biogas

Year	**Policy type***	**Name**	**Content**	**Discussed in**
1997	S/AP	White Paper for a Community Strategy and Action Plan COM(97)599 final	• deployment of biogas and bioenergy in the overall energy policy framework	(Erbach, 2017)
2009	D	Renewable Energy Directive (RED) 2009/28/EC	• objective of 20% share in final gross energy consumption by 2020 • binding national targets for the development of renewable energies • transport: 10% renewable energy target by 2020 • installs roadmaps & support measures • support for developing infrastructure criteria for sustainable biofuels • amended RED contribution of conventional biofuels to the overall share to 7% and mandated a non-binding target of 0.5% for advanced biofuels	(EU Science Hub, 2019; Scarlat et al., 2018)
2012/ 2018	S	Bioeconomy strategy COM/2018/673 final	• anchor the bio-based economy as part of a larger green economy strategy to replace fossil fuels on a larger scale	(Erbach, 2017; Prussi et al., 2019)
2016/ 2009/ 1998	D	Fuel Quality Directive 2009/30/EC	• 6% reduction in greenhouse gas intensity of road transport fuels by 2020	(Bourguignon, 2015; Bourguignon & Vandenbussche, 2017)
2018	D	Renewable Energy Directive II (EU) 2018/2001	• 6% reduction in greenhouse gas intensity of road transport fuels by 2020 • national indicative contributions to EU target • heating and cooling: member States to annually increase energy from renewable sources for heating and cooling purposes (1.3 percentage points, or 1.1 percentage points if waste heat is not taken into account)	(EU Science Hub, 2019; Torrijos, 2016)

			• share for 14% overall renewable energy use in transport. The limit for conventional biofuels remains capped at 7 percentage points while 3.5 percentage points of the target should be reached through advanced biofuels by 2030	
2018	R	Governance Regulation (EU) 2018/1999	• reporting on progress in National Energy and Climate Plans	(Knodt & Ringel, 2019; Ringel & Dopfer, 2018)

*Legend: S-strategy; AP-action plan, D-directive; R-regulation.

Sources (Banja et al., 2019a, Banja et al., 2019b; Bourguignon & Vandenbussche, 2017; Bourguignon, 2015; Erbach, 2017; EU Science Hub, 2019; Knodt & Ringel, 2019; Prussi et al., 2019; Scarlat et al., 2018; Torrijos, 2016)

Banja et al. (2019b) report that by the end of 2017, about 700 support measures for bioenergy were in place in the EU. Two thirds of these were financial support policies, with the remaining one-third divided among administrative, regulatory and other support. Table 2-3 summarizes the policies and measures in place in our focus countries.

Table 2-3: National biogas policies and measures

	Germany	**UK**	**Austria**	**Switzerland**
Support for transport use				
Quota scheme	X	X	X	X
Tax exemptions (e.g. energy tax, carbon tax)				X
Subsidies to consumers for use in transportation		X		
Support in electricity and heating/cooling use				
Investment subsidies to producers/ operators	X	X	X	X
Investment loans under special conditions	X	X	X	
Feed-in tariffs for biomethane injection/ electricity production	X	X	X	X
Feed-in premiums for biomethane injection/electricity production	X		X	
Subsidies to consumers for heating		X		
Tax exemptions (e.g. energy tax, carbon tax)	X			X
Information	X	X	X	X
Biogas production as part of rural development strategies	X		X	
Priority access to national electric grid/gas network	X		X	X

Source: Information summarized in this table is taken from RES LEGAL Europe (RES, 2020), the National Renewable Energy Action Plans (JRC - Joint Research Centre, 2019), Zhu et al., (2019), and the IEA Bioenergy (IEA, 2018a; 2018b).

The closest alignment of policies can be seen in the transport sector, where a biofuel quota is in place in all countries (e.g. the UK Renewable Transport Fuel Obligation, RTFO since 2008; see Ahman (2010) for a comprehensive overview). Here notably the discussion on sustainability issues (emissions as well as Indirect Land Use Changes) had raised strong concerns and led to a high degree of market uncertainly (Scarlat et al., 2018). As a consequence, the EU introduced the focus on advanced biofuels in its revised Renewable Energy Directive (RED II), which served as blueprint for the jurisdictions that we analyze. Quotas specify either a minimum share of biofuel content or a reduction quota of GHG emissions with biofuels. (BMLFUW, 2012; IEA - International Energy Agency, 2018a, 2018b, 2018c). Switzerland provides an additional tax exemption for biogas use in transport.

Biogas use in heating and cooling is supported in all four countries through a broad mix of fiscal support combining investment subsidies/loans, feed-in tariffs/premiums and information measures (labelling). Support schemes for biogas mostly target electricity generation; only 24% of all support measures directly targeted biomass in the heating and cooling sector (JRC - Joint Research Centre, 2017). While policies in the four countries may agree in their support for biogas, national frameworks differ in their regulatory focus.

2.3.1.1 The UK

The UK aims at reaching a share of 15% renewable energies in gross overall final energy consumption by the end of 2020. According to government strategy plans, 12% renewables are to be deployed in the heating and cooling sector and 10% in transport (UK Government, 2017a; 2017b). Biogas installations can receive support for both electricity generation and heat generation. Regarding electricity generation, the quota-based Renewables Obligation (RO) for large-scale renewable power generation ended in 2017 (Ofgem, 2017). For smaller installations below 5 MW, the FIT scheme remains the key support instrument (Maroulis, 2019). With respect to installed capacity, different tariffs are in place. In addition, certain sustainability standards have been set up that continue to apply (Ofgem, 2013).

The UK is alone among the focus countries to offer direct support for biogas in the heating sector (IEA - International Energy Agency, 2018c) through the Renewable Heat Incentive (RHI). The RHI is split into two schemes: the non-residential or “non-domestic” RHI, in place since 2011, and the domestic RHI, in place since 2014. Updates to the RHI were announced in 2016 and fully implemented by 2018 (UK Government, 2020). The domestic RHI supports domestic installation of renewable heat generation (UK Government, 2017b); however, current regulations exclude support for biogas. In contrast, biogas and biomethane are included in the non-domestic RHI segment, covering industrial, commercial, public sector and not-for-profit organizations. This includes hospitals, schools, and district heating schemes (IEA - International Energy Agency, 2018c). Eligible generators receive regular payments over 20 years, distributed in tariff tiers (See Table A1 in the Supplementary Material).

The RHI scheme has been successful in stimulating rapid growth in biomethane uptake (Banja et al., 2019b), raising the number of biomethane plants from one in 2011 to nearly 100 in 2016. Under the non-domestic RHI, eligible projects using biogas directly or through a CHP system can also receive in parallel funding for electricity generation (Renewable Energy Agency, 2019).

2.3.1.2 Germany

The German framework for biogas supports use in electricity generation since 2000 through the feed-in-tariffs of the Renewable Energy Sources Act (RESA) (IEA - International Energy Agency, 2018a). Tariffs are fixed for plants with a capacity lower than 150 kW or established before 2017. All other plants have to participate in a capacity tendering system decreed by the RESA 2017 revision. Terms and conditions for the biannual tendering auctions are set by the Federal Network Agency (Bundesnetzagentur) as grid regulator (BNetzA - Bundesnetzagentur, 2019). Only indirect support is granted for heating use via Combined Heat and Power (CHP), but even it remains negligible.

In principle, the CHP Act (KWKG) can supersede the RESA support by granting a feed-in premium. The government has extended fiscal support to direct feed-in into heating and cooling networks, allowing for feed-in premiums under the Act. As the premium until present has remained lower than RESA support or tendering results, only exceptional cases have made this economically attractive. This might change in the future as the government plans to incentivize “innovative CHP,” including the use of methane as fuel (Bowe et al., 2018). Direct funding for the set-up of biomass installations exists for both private entities and the local public sector via the “Marktanreizprogramm” incentive scheme (Deutsches Biomasse-Forschungszentrum, 2019; Maggioni & Pierroni, 2016).

Adding to the economic support on the supply side, the German policy framework mandates use obligations on the demand side, with the overall aim being to cover 14% of heat demand through renewable energy sources by 2020.

The federal Renewable Heat for Warming Act (Erneuerbare Energien Wärme Gesetz) mandates the use of renewable energies in new buildings. If gas is used for heating, homeowners have to prove that 30% of the heating demand is covered by CHP-based biogas. As regional legislation can tighten and complement national laws, the Renewable Heat Act (Erneuerbare Wärme Gesetz) of Germany's southwest region of Baden-Wuerttemberg applies a similar minimum share of heat provision in the case of building refurbishment, requiring that 15% of heating consumption be covered by renewable energies. Out of this, 10% can be covered by using CHP-based biogas (Ringel & Dopfer, 2018). Natural gas containing at least 10% biomethane could be counted partly into the requirements of the Renewable Heat Act (degree of compliance = 66.7%).

The Biomass Ordinance (Biomasse-Verordnung, 2014) specifies eligibility criteria for biomass support. Whereas the German Energy Law in Buildings (Gebäudeenergiegesetz, GEG) fixes a primary energy factor of 1.1 for green gas – as such being equivalent to conventional gas – the Biomass Ordinance allows balancing with a factor of 0.5 in case the heat use is “locally related”, thus strongly favoring local uses (Bowe et al., 2018). Several additional schemes are in place to support households in switching to renewable-based heating systems.

2.3.1.3 Austria

The Austrian energy and climate strategy (BMNT, 2017a; 2017b) emphasizes the importance of biogas both for natural energy storage and to increase flexibility in the energy markets, especially in regional markets where the uptake of green methane and power-to-gas options have been encouraged (BMNT, 2018a; 2018b). The federal government acknowledges, that “the conversion of natural gas to renewable energy sources (including renewable gas) in the heating market will take a long time, because there are only limited system alternatives, especially in metropolitan areas” (BMNT, 2018a; 2018b).

The Austrian feed-in tariff for power use is regulated by the Green Electricity Act (Ökostrom-Einspeiseverordnung and Ökostrom-Einspeisegesetz - (BMNT, 2018a; BMWFW, 2017; Österreichischer Nationalrat, 2012). Feed-in tariffs are granted for 15 years, decreasing by a rate that depends on the date of application. Preparations are underway to change the feed-in support to a tendering regime.

Subsidies are also available for biogas fed into the public gas grid (BMDW, 2018). Biomethane that is fed into the gas grid and used by a customer in the same region receives a discount of 1 Eurocent/kWh on gas grid charges (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2017).

Self-consumption and injection into the national gas grid are further supported through having the first 25,000 kWh of self-consumed electricity as well as the direct use of biomethane (i.e. not mixed with natural gas) fully or partially exempted from energy taxes and VAT (Maggioni and Pierroni, 2016).

As in Germany, biogas electricity from combined heat and power plants (CHP) is awarded a feed-in bonus. Further investment support for new and modernized biogas plants is granted (Lindorfer et al., 2017; Österreichischer Nationalrat, 2012). Austria also has comprehensive set of support schemes for heating replacements, favoring the use of renewable energies at large.

2.3.1.4 Switzerland

The Swiss Energy Strategy 2050 aims to expand renewable energy into all end uses (Schweizerische Eidgenossenschaft, 2018). The 2018 Energy Act sets indicative values for electricity production from renewable energies for 2020 (4400 GWh) and 2035 (11,400 GWh) (IEA - International Energy Agency, 2018b). Direct biogas support is provided only for electricity generation by the means of feed-in tariffs (BfE, 2017; Schweizerischer Bundesrat, 2016). Tariffs are granted for up to 25 years. Further to feed-in tariffs, investment credits support the installation of biomass plants (BfE, 2018).

Other than sewage and landfill biogas, farm biogas is also eligible for support, provided it does not contain more than 20% gas from energy crops and non-farm residues (Bundesamt für Energie, 2016). Electricity must be certified with regard to quantity, production period, energy source used and plant data by means of proof of origin (Bundesversammlung, 2018).

Several mechanisms of indirect support exist via tax refunds. This notably concerns a refund of CO_2-taxes for feeding gas into CHP-based heating grids (Schweizerischer Bundesrat, 2012) and the exemption of CO_2 and mineral oil taxation for transport uses. Through the CO_2 law, the CO_2 tax on fuels for stationary applications has been set at CHF 96 per ton of CO_2 since January 2018 (IEA - International Energy Agency, 2018b), making a reduction more attractive for plant owners.

Indirect demand-based support exists for the replacement of fossil or direct electrical heating by heating systems with renewable energy or by the connection to a heating network (energy efficiency in building programs). However, conditions differ depending on the cantons (BfE & BfU, 2019). Looking to spur demand, the Swiss biogas association has set up a funding pool for innovative gas-use projects, including methanization (Verband der Schweizerischen Gasindustrie, 2019).

2.3.1.5 Country summary

All four countries support electricity generation through biomethane by economic instruments such as feed-in tariffs, quotas or tenders. Our results show that energy policy has focused chiefly on biomethane's use in electricity generation, and this has operated as central driver for development of national biomethane industries.

For heating, only the UK advances a clear quota mechanism; however, UK policy excludes biogas from receiving support for residential heating use. The German system offers a larger choice menu, but policy is embedded in energy efficiency regulations for new and, for one region, refurbished buildings. In the Austrian and Swiss markets, policy actions for residential heating are limited to indirect support for CHP-based production of heat.

Finally, the transport sector is primarily framed by quotas for biofuels or emission reduction shares, both combined with sustainability targets that favor biomethane as an advanced biofuel.

2.3.2 Products

The strong regulatory focus on electricity generation leaves the voluntary heating markets largely unregulated. As reported in section 2.2, the number of product choices consumers have in each of these markets differs widely: In Switzerland, 188 biomethane-based heating products are offered, in Germany 127, in Austria 25, and in the UK only 24.

Our analysis of product attributes focused on those that influence the sustainability of biomethane products. These are also the attributes most important to consumers, and include biomethane content, geographical origin, and the feedstock used to produce the gas.

Figure 2-1 shows the number of products by biomethane content. Tariffs with 10% biomethane content dominate the market in Germany and the UK. In Switzerland and Austria, the distribution between low-content and high-content tariffs is more even. The Swiss market stands out with its high share (29%) of 100%-tariffs.

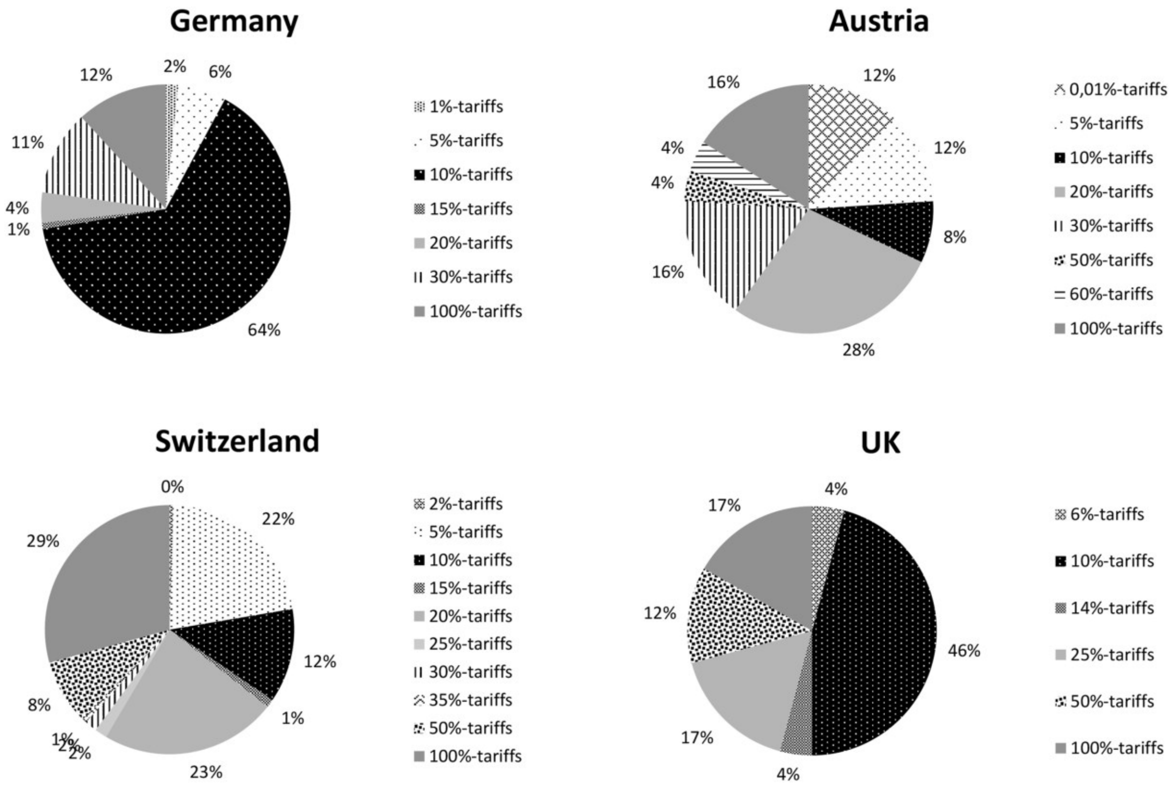

Figure 2-1: Number of tariffs by biomethane share in the four markets

Table 2-4 presents our results on the geographical origin of the biogas. Here, we show only biomethane products in Germany and Switzerland. In the UK, none of the providers revealed any information about the origin of the biogas. In Austria, all products were from regional sources. In Germany, we could find information about the origin in fewer than one in three (29%) products: 17% had a regional origin and 12% a national origin. Swiss providers were far more transparent about the origin of their products: for 81% of the products under review, we were able to identify the geographical origin, which was evenly distributed between regional, national and international.

Table 2-4: Share of tariffs by geographical origin in Germany and Switzerland [%]

	Germany	**Switzerland**
Regional	17	31
National	12	22
International	0	28
Origin unknown	71	19

A third attribute that matters to consumers is the feedstock that fuels biogas production. As Table 2-5 shows, German providers again scored low in transparency on their products: In 54% of the German products under review, providers did not disclose the feedstock. In Austria, purely waste-based products and products based on a mix were equally important. In Switzerland, a clear majority of the products were based on waste. In the UK, half of the tariffs were based on waste. For 38% of UK products, providers did not disclose information on the raw material for the biogas underlying their tariff.

Table 2-5: Share of tariffs by feedstock type [%]

	Germany	UK	Austria	Switzerland
Waste	20	50	40	86
Mix	24	8	40	3
Energy crops	2	4	0	0
Feedstock unknown	54	38	20	11

Overall, we can summarize our product analysis by noting that both Germany and Switzerland offer more than one hundred tariffs, although in Switzerland, the tariffs are only available regionally. The UK market, although a large gas market, offers only 24 products, on par with the much smaller Austrian market.

The German and British markets show a predominance of products comprising 10% biomethane, while the other markets show an even distribution of products with different biomethane contents ranging from 1% to 100%.

German providers tend not to disclose either the geographical origin or the feedstock of the biogas plant supplying the biomethane. For those tariffs with such information, the distribution is fairly even between regional and national origin and between tariffs based on waste and those based on a mix of waste and energy crops.

Austrian tariffs are evenly distributed between regional, national and international origin. Like Germany, about half of the tariffs for which information is disclosed are based on waste, the other half on energy crops. Switzerland shows a predominance of purely waste-based tariffs.

2.4 Conclusion and policy implications

We analyzed the regulatory frameworks for biomethane use in the UK, Germany, Austria and Switzerland against the biomethane product offerings in the respective heating markets, seeking insight into the impact of policy frameworks on the development of the voluntary market for biomethane as a heating fuel.

2.4.1 Connecting markets and policies

Our analysis has shown that the use of biomethane for residential heating is largely untouched by regulation in the four countries. Only two exceptions were found: First, the UK's RHI excludes support for biogas in residential heating, but does support biomethane in non-residential installations.

Inconsistent demand-side policy support was pointed out by stakeholders in a recent study (Richards & Al Zaili, 2020).

Second, Germany allows households to use CHP-based biomethane to fulfill the regulatory requirements for renewables use. However, previous research has shown that biomethane is not an attractive option from a financial point of view for fulfilling said legal requirements (Gawel et al., 2014).

2.4.1.1 Competition of voluntary heating markets with regulation-driven electricity generation and transport sectors

The most obvious finding to emerge from our policy analysis is that support for biogas and biomethane has been geared to the production of electricity or to transport. Recently, support has been cut back, but it was rather generous from about 2004 to 2014. This meant little to no need existed for biomethane producers to develop other sales channels.

Overall, we are led to the conclusion that state-led-support has crowded out the opportunities that might have arisen in voluntary markets and has prevented suppliers from prioritizing product innovations and large-scale marketing into voluntary markets. This conclusion is supported by the fact that in Germany, for example, the majority of the biomethane in the market, almost 8000 GWh, i.e. circa. 80% of the German production, goes into CHP units receiving FIT for their electricity while only 500 GWh goes into the heating sector (Völler & Reinholz, 2019).

2.4.1.2 Indirect influence of regulation in other sectors on product attributes in voluntary markets

Another important finding of our analysis is the indirect influence of policies on product offerings in the heating market. We found that 65% of all products in Germany had a biomethane content of 10%, which seems to be attributable to the Baden-Württemberg region's Renewable Heat Act. The second most often offered percentage, accounting for 11% of all tariffs, is 30%, the level set by federal regulations. The fact that the majority of tariffs are crafted in response to state-level law shows that it influences demand and consequently supply more strongly than the federal-level regulations, despite the fact that the state of Baden-Württemberg is home only to 13% of the German population. The federal policy stipulating a mandatory combination of biomethane and CHP units in the residential sector seems rather unsuccessful. This is not surprising in the light of earlier research showing that the cost of heating with biomethane using CHP is the worst option for a single-family home and only the third most attractive for apartment houses (Gawel et al., 2014).

In the other three heating markets, we could not detect any influence of policy instruments on the biomethane percentage of offerings. Why nearly half of all tariffs in the UK have a biomethane content of 10% cannot be directly traced to UK policy. Perhaps providers consider it a psychological threshold for consumers.

Only in Austria did we find influence from the regulatory framework on the geographical origin of biomethane products. In Austria, biomethane plants receive a refund on the gas grid charges if their gas is used by a customer in the same region (Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2017). This clearly is an incentive for regional products and offers a simple explanation for why Austria has only regional products.

We find regulatory influence on the input materials used as feedstock in biogas production in all countries. Under the German REA, electricity produced from biogas based on energy crops has received favorable FIT in comparison with gas based on waste. This has increased the crowding-out effect of subsidies for biogas plants running on energy crops; even though 87% of the biomethane from facilities in Germany is generated from energy crops, only a low share of this biomethane is channeled into heating.

In Switzerland, nearly 150 GWh, which is a large part of the biomethane sold in the country[2] is imported from the UK and Denmark (Völler & Reinholz, 2019), which limits the Swiss regulatory influence on input materials. The majority of biogas produced in Switzerland stems from waste water treatment plants (Bundesamt für Energie BFE, 2015). If farm biogas is to be used for electricity production under the Swiss support system, its feedstock may not consist of more than 20% energy crops or non-farm residues (Bundesamt für Energie, 2016).

In the UK, the government evaluation notes that the use of waste-based feedstocks increased following the 2016 RHI reform announcements. This may, to some extent, have accelerated an ongoing trend, as reductions in tariff levels have led applicants away from the more expensive crop-based feedstocks (UK Government, 2020).

Summarizing the conditions in the four countries, we can say that though there is little direct regulation of the voluntary markets, our results do identify indirect influence from policies aimed at supporting competing applications in electricity generation and transport. This includes influence on the biomethane content, geographical origin, and feedstock of biogas-based products in the voluntary heating markets.

2.4.1.3 Policy influence on market development

Detailed historical data is available showing how the regulatory framework in Germany has influenced the development of the biomethane market. Over the years 2011–2014, the compound annual growth rate (CAGR) for biomethane fed into the public grid was 36%; over the years 2015–2018, it dropped to 5%, a direct effect of the 2014 RESA reforms that reduced support for biomethane-based electricity generation. The four years of robust growth in the biomethane market were dominated by electricity generation, which added about 5000 GWh until 2014/2015. Over the same time, biomethane use for heating grew merely 200 GWh, from roughly 300 GWh to 500 GWh.

The German market seems to be in a consolidation process: A study based on data from 2014 found 170 biomethane-based tariffs (Herbes et al., 2016) but our study only identifies 127. A

[2] Ca. 190 GWh of biomethane are produced in Switzerland and fed into the gas (Bundesamt für Energie BFE (2015)).

comparison with the voluntary market for green electricity hints at the low strategic priority of voluntary markets for gas providers: Nearly 80% of the roughly 1200 electricity providers in Germany offer a renewable electricity tariff (Hauser et al., 2019). But even after more than half a decade of biomethane in the voluntary market, out of 1047 gas providers (Statista, 2020a), only the 83 providers offering the 127 products in our sample offer a biomethane-based gas tariff, a mere 8%. So 92% of the gas providers in the heating market consider it unattractive to enter this market.

2.4.2 Policy implications

Before discussing how a policy framework could drive increased utilization of biomethane in household heating, the overall question emerges whether the heating sector should be prioritized at all. This is a strategic decision to be made by policy makers in all jurisdictions analyzed.

From our point of view, this decision can be taken against three criteria: i) the relative environmental merits of using biomethane for electricity production in the transport sector and in heating; ii) the long-term effects on heating infrastructure; iii) the chances to decarbonize the heating sector in other ways than using biomethane.

Regarding the first aspect, Vogt (2008) show that the reduction of greenhouse gas emissions is largest when using biomethane for the production of electricity (CHP). Using biomethane in transport ranks second and using biomethane in the heating sector as a substitute for natural gas comes in third by far (Vogt, 2008). A more recent study confirms the higher mitigation of CO_2 emissions in the electricity and transport sectors compared to the heating sector (Lauf et al., 2019).

Regarding the long-term effects on the heating infrastructure, fostering the use of biomethane in the heating sector could result in a lock-in effect. This lock-in effect could result from households replacing an oil-fired boiler with a gas-fired boiler using biomethane. If preventing this lock-in takes priority, policies need to exclude new heating systems.

Turning to the last issue, we have to take into account the long renovation cycles of heating infrastructure. Heating systems often run for 20 years or longer. If accelerating decarbonization of the sector is a political priority, policy makers need to support the use of renewables in the existing heating infrastructure. For this, biomethane is realistically the only option.

Thus, the strategic decision depends on political priorities. If a faster decarbonization of the existing heating infrastructure takes precedence, channeling biomethane into the heating sector is an adequate policy goal. If the long-term perspective on environmental effects and mitigation cost is the guiding principle, the existing focus on supporting the utilization of biomethane in power generation and the transport sector is a good approach.

As a second step – if accelerating decarbonization of the heating sector is key and policy makers want to channel biomethane into this sector – policy makers will need to consider appropriate policy interventions: What policy actions could successfully incentivize households to use biomethane-based products? The analysis of the availability of market offers and the differing regulatory frames can act as a guiding indicator for this.

The Austrian framework seems to provide enough incentives for local offers. Looking into the Austrian refund system might be of interest for Swiss market development which is presently largely covered by imports. If developing a national biomethane industry is a political aim for the Swiss authorities, the Austrian scheme is worthwhile investigating in.

The various reforms in the UK seem to have impacted the market only to a limited extent. If again the political decision is to foster biomethane-based heating, a straightforward approach would be including residential heating in the RHI.

In Germany, a successful policy framework should foster a fuel switch with existing technologies rather than just targeting the relatively low number of households that replace their heating system or build a new home for themselves.

Second, the mandatory biomethane content should not be too high. Past research has shown that in Germany a tariff containing 10% of biomethane leads to a price increase of 10% and a 100% biomethane tariff means in many cases almost a doubling of heating cost (Herbes et al., 2016).

To summarize, it seems promising to enlarge the focus on new buildings and households to existing buildings that require a change in heating technology and at the same time to lower the requirements regarding biomethane share and the use of CHP.

This could be achieved with two types of policies. Demand-side policies could target the households, mandating them to source a certain percentage of their energy from renewable sources. Alternatively, as supply-side policy, natural gas providers could be obliged to fulfill a renewable quota in the gas products they offer, an approach also recommended by Richards and Zaili (2020).

In any case, a successful policy framework should oblige providers to provide all information consumers deem pertinent to their decision making. This is a desideratum for all four countries. Past research has established the product attributes important to consumers, so information on these attributes that is easy to find and easy to understand, preferably in a standardized form for all providers, would help consumers make choices in line with their preferences. Providing information is especially pertinent given the low level of knowledge (Richards & Al Zaili, 2020) and the high level of insecurity (Herbes et al., 2018b) felt by consumers when asked about biomethane.

We would also like to emphasize what Zhu et al. (2019) called a “clear vision” (Zhu et al., 2019, p. 10). In Germany, for example, the government tried to foster the voluntary market by incentivizing households to source biomethane, but subsidized biogas plants so heavily for channeling their gas into electricity generation that the voluntary market was crowded out for many years. This contradiction is unique among the four markets.

2.4.3 Limitations and avenues for further research

One limitation of our analysis is that our data only allowed us to look at the number of biomethane tariffs that exhibit a particular attribute. However, we do not know how much of that product is sold in the market. But, given the fact that, especially in the Swiss and German market there are a large number of providers and that regional providers historically have a strong position in both countries, it is unlikely that an overwhelming market share goes to very few products, which if this were the case would result in a very different picture.

Future research could look into the deliberations of the providers on their product strategies. How strongly do they perceive their strategy to be influenced by regulation, which future position do they see for voluntary markets as a sales channel and how do they picture their customers' preferences?

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3) Invisible, intangible, irrelevant, yet inevitable? Qualitative insights into consumer perceptions of heating tariffs and drop-in renewable gases in the German domestic heating market

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Abstract One of the key challenges of increasing renewable energy use is consumer demand. In the residential heating sector, where long-lived fossil-fuel systems are slow to be replaced, consumer demand for drop-in renewable gases like biomethane or Synthetic Natural Gas could play an important role in short-term decarbonization. As this sector is a major emitter of CO_2 in Europe, robust green demand could be key to fulfilling the targets set in the Paris Agreement. Yet existing research focuses on the supply side and technical aspects of renewable gases, leaving the demand side and consumer preferences for these gases largely neglected. To close this gap, we conducted a qualitative study based on two empirical strands: 22 interviews with heating consumers, and a set of interviews and focus groups with 27 industry experts. The study was situated in Germany, one of the world's largest biogas producers.

Our results show that choosing a heating tariff is a low-involvement decision, but one made by a complex calculus where the environmental benefits of renewable gases count positively, but large-scale biogas production and perceived energy crop monocultures count negatively. SNG is still largely unknown and regarded neutrally. Industry experts evaluate voluntary markets for renewable gases as small, cost-driven and made up of consumers accustomed to low-cost products. Our insights on consumers who have the decision-making power over their heating tariffs can help policy makers support voluntary renewable energy markets and provide energy practitioners with approaches to increasing consumer engagement with their products.

3.1 Introduction

With its decision to cut greenhouse gas (GHG) emissions by at least 55 % by 2030, the European Commission renewed its ambition to hit the target levels set in the Paris Agreement (European Commission, 2020a). European climate policy prioritizes cutting GHG emissions, increasing the market penetration of renewable energy and increasing energy efficiency (Bertelsen & Vad, 2020) Progress towards these goals must include the residential sector, which in 2018 accounted for 26.1 % of the final energy consumption in the European Union (Eurostat 2020). Within that sector, 78.4 % of the final energy consumption goes to heating, with 63.6 % going to heat homes and 14.8 % to heat water (Eurostat 2020).

Many countries in Europe contribute to these aggregate numbers. In Germany, for example, the latest energy figures show heating homes and water accounting for 82.9 % of the final energy consumption by the residential sector; in the Netherlands, the number is 80.1 % and in the UK, 79.9

% (Eurostat, 2020). The numbers are similar throughout Europe, as the heating sector in most countries accounts for the lion's share of residential energy use, and hence of the associated CO_2 emissions. This makes the sector a prime target for decarbonization.

It is estimated that 75 % of the building stock in Europe is considered as not efficient (European Commission, 2020a), which makes accelerating renovation rates an obvious approach to lowering CO_2 emissions. However, renovation rates hover around 1 %, and speeding up renovation cycles is not easy. But immediate reductions in fossil-fuel consumption can be realized using drop-in heating fuels coming from renewable sources (Herbes et al., 2021a). Although some progress has been made in this direction, fossil fuels remain the primary energy supply for the building stock in Europe (70 % in 2015), with much of these fuels being imported (Bertelsen & Vad, 2020). This has raised, besides environmental issues, also longstanding security concerns (Le Coq & Paltseva, 2009) highlighted by the recent debate over the pipeline Nord Stream 2. The debate is particularly divisive because the preferred fossil fuel for heating in Europe is natural gas. Admittedly, the range of dependency on gas is large: Sweden, for example, heavily relies on district heating grids, with natural gas accounting for only 0.6 % of the final energy consumption for residential heating (Bertelsen & Vad, 2020; Eurostat, 2020). More typical, though, are gas-hungry countries like Germany (48.1 %), the UK (74.7 %) or the Netherlands (86.2 %) (Eurostat, 2020). Accordingly, the typical heating systems used in Germany in 2019 were: gas-based central heating (35.7 %), gas-based single-story heating (9.8 %), oil-based central heating (25 %), district heating (13.9 %) and individual heaters (e.g. electricity-based storage heating, 6.1 %) (bdew - Bundesverband der Energie- und Wasserwirtschaft, 2019). While gas remains the undisputed main energy source in existing housing stock (and oil-based heating systems gradually decrease) (bdew - Bundesverband der Energie- und Wasserwirtschaft, 2021), electricity-based heat pumps are increasingly gaining ground in new residential construction: 2020 was the first year with more heat pumps being approved than gas-based heating systems (35.5 % vs. 33.2 %) (bdew - Bundesverband der Energie- und Wasserwirtschaft, 2022). The availability and therefore the reasons for choosing a heating system are manifold and e.g. depend on structural and historical differences: Federal states and areas with a high population density and high shares of apartment buildings typically rely on grid-based energy carriers like gas or district heating. Oil-based heating systems can be typically found in less populated areas, where the gas grid is usually less developed (bdew - Bundesverband der Energie- und Wasserwirtschaft, 2019). Furthermore, it should be noted that the decision-making authority for a heating system (and hereafter for a specific tariff) is strongly correlated to the ownership of the residential property: Tenants (which make up more than half of all households in Germany (Statistisches Bundesamt, 2019)) typically cannot decide on these aspects.

That natural gas is the dominant fuel used by existing infrastructures in the European Union makes necessary an alternative path to decarbonization besides efficiency measures. That path is to inject renewable gas directly into the gas grid (Gielen & Bazilian, 2021). However, the share of renewable gas in the grids in Europe is still marginal (Herbes et al., 2021a; Scarlat et al., 2018). Two feasible approaches exist for replacing natural gas with a renewable source. The first and most common is upgrading biogas to biomethane, which can then be injected into the grid or used locally as a vehicle or heating fuel (Gas Infrastructure Europe & European Biogas Association, 2020; Scarlat et al., 2018). Numbers from 2018 put the total output from European biomethane plants at 22,787 GWh, somewhat concentrated in Central and Western Europe with 232 plants in Germany, 131 in France, 80 in the UK, 70 in Sweden and 53 in the Netherlands (Gas Infrastructure Europe & European Biogas Association, 2020). The second and more recent approach to greening the gas sector is so-called Power-to-Gas (PtG) technology. This utilizes surplus electricity from renewable sources to produce hydrogen through electrolysis; the hydrogen can then be injected into the natural gas grid (only to a certain degree) or, using an external carbon dioxide source like a biogas plant, be converted to methane (methanation). This is called Synthetic Natural Gas (SNG), and it can be used just like regular natural gas (Götz et al., 2016; Horschig et al. 2018; Winquist et al., 2021).

Biomethane and SNG offer great potential for decreasing the CO_2 intensity of the residential heating sector without the long delays caused by lengthy renovation cycles. Both gases enjoy practical advantages over, say, hydrogen, where the market ramp-up has only just begun and infrastructure is in statu nascendi (European Commission, 2020b).

So we must note with some concern that recent analyses of markets for renewable electricity (Herbes et al., 2020) and biomethane (Herbes et al., 2021a) have shown that state-led support in Europe has more often hindered rather than supported the development of voluntary renewable energy markets. It is paramount that policy makers not repeat these mistakes in the emerging market for SNG. We are convinced that the starting point both for tailoring state-led support schemes and for developing energy marketing strategies is a deeper understanding of consumer preferences and their subjective logics.

That understanding is not to be found in the literature. Research on marketing biomethane and SNG has focused on the supply side (Budzianowski & Brodacka, 2017; Götz et al., 2016; Herbes et al., 2016, 2021a; Lehner et al., 2014; Parra & Patel, 2016). For example, in their comparative study of biomethane offerings in the UK, Germany, Austria and Switzerland Herbes et al. (2021a) showed the complexity of the tariff portfolio consumers can choose from. The offerings vary in several aspects, e.g. biomethane share, feedstock or geographic origin, potentially overwhelming consumers in their decision-making. The focus on the supply side leaves open many questions on the demand side, especially questions that focus on energy users and the decisions they make about renewable technologies. The relevant body of literature is small: Herbes et al. (2018a) and the slightly dated study from Forsa (2012) covered consumer preferences regarding biogas and biomethane in France and Germany, respectively. They found significant knowledge gaps as well as preferences for biogas from agricultural residues and waste. In a comparative study of consumers in Germany, France and the US that examined perceptions of biomethane as a raw material for bio-based packaging (Herbes et al., 2018b), biomethane rated lower in desirability compared to other materials, and reservations against biomethane again surfaced. Research on the demand side of SNG is lacking entirely. Due to the scarcity of research on consumer preferences for renewable gases, we can also briefly consider results from the far more numerous studies on consumer preferences for green electricity. These have shown that consumers prefer products with high renewable content; from local sources and local providers; from energy cooperatives; and with eco-labels (Bigerna & Polinori, 2015; Herbes et al., 2015; Ma et al. 2015; Oerlemans et al., 2016; Sundt & Rehdanz 2015). Soon and Ahmad (2015) in their meta-analysis showed that willingness-to-pay for renewable energy from biomass is lower than for all other sources, except hydro power.

From the more general literature on marketing (renewable) energy, we know that selecting energy products is regarded as a low-involvement decision, meaning consumers tend to limit their efforts when choosing one product over another (Friege, 2017; Friege & Herbes, 2017). This insight helps explain the relatively few households who leave their incumbent suppliers of natural gas; on average, from 2013 to 2017, the supplier switching rate per annum was only 12.4 % in the UK, 9.6 % in France, and 8.8 % in Germany (Council of European Energy Regulators, 2019). Taking this one step further, we can also frame the selection of a (renewable) gas tariff as one form of sustainable consumption. In the literature, there are plenty of models and theories used in this field: e.g. the Value-Belief-Norm Model (VBNM) (Stern, 2000), the Norm Activation Model (NAM) (Schwartz, 1977), the ubiquitous Theory of Planned Behavior (TPB) (Ajzen, 1991), theories of social practice (Warde, 2005; Welch & Warde, 2015) or the Motivation-Opportunity-Ability Model (MOAM) (Blumberg & Pringle, 1982; Ölander & Thøgersen, 1995). For an overview see Jackson's excellent review of several theories and models on consumer behavior and behavioral change (Jackson, 2005). In the discussion we will reflect on these models and their applicability in our specific case.

The high number of households choosing to stay with their natural gas suppliers rather than switching to a renewable tariff and the lack of research on the consumer side of the market for renewable gases prompt our three research questions:

1. What factors lead consumers to select a specific heating tariff?
2. What perceptions, preferences and reservations do consumers have with regard to gas from renewable sources?
3. How do experts in the biomethane and SNG industries assess consumer perceptions?

Questions one and two investigate demand-side perspectives directly, while question three queries supply-side experts on their picture of the demand side. To address all three, we situated our study in Germany, where the relationship between society and renewable energy technologies has years of development behind it. The first two research questions are essential for both researchers to better understand consumer behavior in this specific field and for providers of renewable gas tariffs to gauge their marketing mix. As our brief review of the literature has shown, neither of the questions has hitherto been answered satisfactorily. The third research question helps us to develop a more robust understanding since the experts have a view on consumers that extends beyond our consumer sample. We aim at making a contribution to scientific literature by providing new insights into the factors that drive consumer behavior regarding renewable gases and picturing their views on these products.

Given the novelty of our research focus, we opted for a qualitative procedure, as we cannot build upon a solid body of previous research that might serve for deriving hypotheses. Moreover, we are interested in subjective logics, and these are best examined through the openness of a qualitative study (Jones et al., 2017).

The remainder of this study unfolds as follows: First, we provide insights into our research design and methods. Second, we present the results of our interviews and focus groups. Last, we discuss our results and offer conclusions.

3.2 Material and methods

Our study uses data from two sources: First, through a series of 22 qualitative interviews with private heating consumers, we collected data on the consumer perspective. Second, through three preparatory expert interviews and three focus groups with a total of 27 industry experts from the biogas, biomethane and SNG (PtG)-sector, we collected data on the industry perspective of the demand side.

Two reasons lie behind our qualitative approach. First, it "…offers a means of providing an in-depth, discursive forum for exploratory research and has been used successfully to discover more about the nature of expert and lay opinion of a number of emerging technologies." (Jones et al., 2017, p. 285). This approach has already been used to study consumer perceptions of biomethane in France (Herbes et al., 2018a), of carbon dioxide utilization technologies in the United Kingdom and Germany (Jones et al., 2017) and of hydrogen technologies (Ricci et al., 2008). Our second reason is based on the knowledge gaps identified by previous research on biomethane. Combined with the recent emergence of SNG technology, we reasoned that consumers would have limited knowledge of renewable gas technologies. So to avoid pseudo-opinions (Jones et al., 2017), we wanted to allow for interactions and clarifications during the interview. The one-on-one setting of an interview also removes barriers that might limit an interviewee's willingness to speak in a group setting (Jones et al., 2017). By contrast, a group setting benefits the expert focus groups "…by constructing a social context in which participants can collectively generate, negotiate and express perceptions and meanings […]" (Sovacool et al., 2018, p. 29).

Our study was situated in Germany, where biogas technologies are well developed and a partially developed voluntary market for biomethane exists in the heating sector (Bowe et al., 2018). However, we consider our research design and also our results (at least partially) applicable to other (European) countries, such as the Netherlands, Italy, Switzerland, Belgium or the UK, where dependency on natural gas in the heat supply prevails (Bertelsen & Vad, 2020; Eurostat 2020) as well as similar heating systems in private households are used (Association of the European Heating Industry, 2020). Furthermore, as laid out in Herbes et al. (2021a), cross-national transferability also arises through both a close (direct and indirect) relation to the European Union legal framework and comparable approaches to regulating biomethane use for heating.

3.2.1 Qualitative interviews

3.2.1.1 Data collection

We drafted an invitation to an interview study, advertised as dealing with "…attitudes of (potential) consumers towards biomethane and synthetic methane, which can be used for heating and as a fuel for vehicles." We explicitly did not ask for prior knowledge, nor were incentives offered so participation would be voluntary. We posted the invitation on relevant online forums, sent it to personal contacts, and circulated it through a call published by the grant program coordinator. In all, 22 people agreed to participate; we designate them Interview Partners (IPs). Table B1 (see Appendix) summarizes their most salient socio demographic attributes as well as their residential and heating status.

The recruitment strategy led to a large share of well-educated interviewees and property owners. However, this was considered adequate since the ability to decide for a specific heating tariff is strongly correlated to owning property, and that with higher incomes and education. We did, however take steps to ensure a broad perspective by including tenants in our sample. Furthermore, we also included persons in our sample who are currently not using a gas-based heating system. During the interview process, it became obvious that focusing on gas-users only would have been too narrow: We would have missed the views and evaluations of users of other widespread heating technologies, who might be future users of a gas-based heating system (e.g. when updating an outdated oil-based heating system or when moving to another house). Our sampling procedure was oriented on the "Theoretical Sampling" approach as developed by Glaser & Strauss (2005), where selecting interview partners is closely related to the insights from the previous interviews (Walter, 2020), combined with elements of deductive sampling (as e.g. described in Przyborski (2014)) and snowball sampling (Walter, 2020).

The interviews were conducted between April and July 2020 by three trained interviewers. Owing to the Covid-pandemic, the interviews were conducted using MS Teams (ten interviews) to allow visual contact between interviewer and interviewee. In eleven cases, MS Teams was not available or not working, and so we used a telephone. One interview was conducted face-to-face per the explicit request of the interviewee. The average duration of the interviews was 66 min, with a minimum of 35 min and a maximum of 115 min.

In the interviews, we used a semi-structured approach. The guideline was developed based upon the pertinent literature (e.g. Herbes et al., 2016, 2018a, 2021a; Herbes & Friege, 2017) and covered the following topics:

- Introduction to the project
- Information on data protection and declaration of consent
- Interest in own energy supply and prior knowledge of biogas and SNG(PtG)-technologies
- Decision process for a heating system and heating tariff
- Evaluation of biomethane and SNG
- Evaluation of alternative and new residential heating systems (e.g. contracting and district heating)
- Demographic information

Each segment was structured by central questions, which, if necessary, were followed up by detailed questions. When it was necessary to explain biomethane or SNG, standardized text segments were used so all interviewees were informed in the same way. The interview guideline is available in the supplementary material (Appendix B2). All interviews were conducted in German, recorded using an external recording device and transcribed by a professional transcription service provider.

3.2.1.2 Data analysis

We developed a category system to analyze the transcripts. To do this, we applied an inductive approach based on the Grounded Theory of Corbin and Strauss (2015), complemented by a deductive approach following Kuckartz (2018), to derive a set of categories from four of the transcripts. The emerging category system was then tested by three coders (same as the interviewers) on a total of four other interviews (not those used to develop the category system), which were coded successively. Deviations and ambiguities were discussed and resolved by the team and the category system was adjusted accordingly.

The final category system was then used by the three coders to code all the transcripts. We used the program MaxQDA (Kuckartz & Rädiker, 2019) to develop and apply the category system. For the final data analysis, we used Qualitative Content Analysis and applied a content structuring approach following Mayring (2015). The resulting coding scheme can be found in the supplementary material (Appendix B3).

3.2.2 Focus groups

3.2.2.1 Data collection

The focus groups were embedded in the larger context of the project from which this study stems. The purpose of these groups was to analyze existing business models and develop potential future models along the biogas, biomethane and PtG (SNG) value chains as well as to identify problems and challenges associated with these models. This approach was guided by the Business Model Canvas framework of Osterwalder and Pigneur (2013).

We started with three preparatory interviews with four experts, each lasting from 52 to 102 min. These were conducted to gather initial ideas, inputs and business models. These first inputs were then discussed and developed further in three focus groups, which took place in July 2020. Each group met for approximately 2 h. The first one was attended by nine, the second and third by seven experts.[3] Following Döringer (2021, p. 265), we identified experts as individuals "considered knowledgeable in a particular subject and [who] are identified by virtue of their specific knowledge, their community position, or their status." The experts in our study covered the biogas, biomethane and PtG value chain: representatives from the areas of plant construction, plant operation, marketing and trade, industry associations, product certification, research and development as well as financing all were present. Appendix B4 summarizes their professional sectors and functions within the specific company. The participants were recruited via e-mail through the contacts of all consortium members in the project.

Given the pandemic constraints, all interviews and focus groups were conducted online using MS Teams. Again, all focus groups were conducted in German, recorded and the audio tracks then transcribed by the same transcription service provider.

3.2.2.2 Data analysis

The specific format of the focus groups and the preparatory interviews provided us with rich and diverse data. The data for this study came from those segments in the transcripts that explicitly dealt with experts´ perceptions of users in the private consumer segment. This data material was then exported and analyzed, again using Qualitative Content Analysis and applying a content structuring approach, as developed by Mayring (2015). This export and analysis was also carried out using MaxQDA (Kuckartz & Rädiker, 2019). Again, the resulting coding scheme can be found in the supplementary material (B5).

3.3 Results

3.3.1 Factors driving consumer decisions for a specific heating tariff

The central factor driving consumer decisions for a heating tariff is cost. One third of the interviewees consider cost in their decision, distributed equally between gas and non-gas users. Looking deeper, we found that especially cost-sensitive gas users tend to regularly change their gas provider: "*For example, I changed my gas supplier because the basic fee was too high for me. So I changed to another one.*" (IP06)[4].

Interestingly, often it was not the tariff itself or its features that formed the basis for a decision, but rather the provider. Here, regionality was deemed important: "*So regionality is not entirely unimportant to me, that's why we get our supply from the regional supplier.*" (IP04). Another supplier-related aspect that stood out was security of supply, reliability and trust: "*And with these other offers and so on, I've heard so many bad things about them, that you sign contracts and they*

[3] In the further course, the abbreviations EX1–3 will be used for the preparatory expert interviews and FG1–3 for the focus groups.
[4] All interview paraphrases in this study were translated from German into English by the authors.

can't deliver afterwards, and stories like that." (IP09). Less frequently mentioned were the offering of renewable energies, service quality, and preferences for specific legal forms. These aspects were especially relevant for interviewees who had had the same provider for years.

Three interviewees indicated they weigh environmental and climate concerns when choosing a tariff: "*And of course that costs a bit more, but for the sake of the environment we have always chosen this product [...]*" (IP14). In this context, four interviewees bear mention: Though all four already source biomethane (at least partially) or have opted for an "eco-gas" product (natural gas with compensation for related CO_2 emissions), none were sure about the specific composition of their gas product: "*The tariff, good question. I think it's the complete eco tariff. I don't even know if there are different gradations, but we get completely, one hundred percent, I mean, that's this one hundred percent eco gas tariff.*" (IP22). We also found this unawareness among regular gas users: "*With gas, I don't really know where it comes from. (...)*" (IP06). There were even two cases of complete indifference: "*I pay the bill, I don't care where it comes from.*" (IP18).

Our results suggest that there are certain segments among the interviewees, i.e. provider-centered (their main calculus relates to the provider rather than the product), environment-centered (trying to minimize their environmental footprint), status-quo-centered (not interested in any changes) and price-centered (driven by economic and monetary considerations). From a more general perspective, we characterize the heating tariff decision as one of low involvement. The calculus is driven by cost considerations and/or relations with the supplier, but it is applied with little thought or awareness, even indifference.

3.3.2 Consumers´ perceptions, preferences and reservations regarding methane from renewable sources

Turning to the core question of how consumers perceive renewable gas, we first asked the IPs if they had – prior to the interview – experience with either of the underlying renewable technologies, biomethane or SNG, i.e. biogas plants or PtG-plants. Of the 22 IPs, almost two-thirds had some prior knowledge about biogas. Interestingly, this prior knowledge was often related to personal involvement either locally or regarding their own profession: "*Biogas plants are more common, because you can see them just here -we live, let's say, relatively rural and there you can see from time to time at some farms the large containers, where biogas is produced […].*" (IP09). In contrast, less than one third of the interviewees had prior knowledge of SNG, most having never heard of it. Interestingly, the interview itself prompted three interviewees to seek information on the underlying technologies.

Given the minimal awareness of PtG-technology, it is not surprising that prevailing perceptions of SNG technology were neutral. IPs were mostly uncritical and driven by openness to new technologies. However, we did find two critical assessments, focusing on efficiency losses, high costs and the uncertain availability of surplus electricity from renewable sources.

Prevailing perceptions of biogas technology were multifaceted. A slim majority of the interviewees were neutral and uncritical. These were joined on the one hand by four interviewees who emphasized the positive value of biogas technology; comments here focused on the use of waste and the renewable origin: "*I have always thought that it is a good thing to produce biogas from waste, from manure, and then use it to generate energy.*" (IP03). On the other hand, we also heard several critical comments. These revolved around large-scale biogas plants, maize monocultures, the so-called "misuse" of crops (fuel vs. food debate), the application of heavy machinery, long arrival routes, loss of biodiversity, and dependency on federal subsidies: "*Yes, the whole biogas thing, it's all too artificial for me. It is necessary and it is right, but it is purely only designed for huge machines and monocultures. I don't really like that. For me, it's no longer really 'bio'. It's the money machine for farmers.*" (IP08). Interestingly, more than half of these critical comments came from interviewees who are in some kind affected by biogas infrastructure in their vicinity (e.g. biogas plants or farmland).

After having received brief information on biomethane from the interviewer (see Appendix B2), interviewees were asked about their general interest in the product. The overwhelming majority – 19 of 22 – IPs indicated their general interest. The reasons were manifold, ranging from environmental awareness and the positive effects of reduced CO_2 emissions to the usage of waste material. However, some restrictions were perceived, e.g. ambiguities regarding delivery options: "*But I don't know if there is a possibility to have the biomethane delivered to our house.*" (IP06) or system compatibility with the existing burner with "another" product (IP17) or security of supply (IP18). Then there were the interviewees who signaled no concrete interest, due to unavailability of gas in the building, strong preferences for the own/another energy carrier, or simple old age: "*Yes, I could say now, due to my age probably, I will no longer think of switching.*" (IP11).

When asked for specific factors influencing their evaluation of biomethane, costs were again central: More than three-quarters of the interviewees consider cost important. Only one interviewee stood out as an exception: "*So for me, now with natural gas, the price didn't play a role, but we have already, yes, we have always opted for renewables, and for me the price would not have been a deciding factor.*" (IP22). This statement signals a clear willingness to accept price premia. We found this willingness in nine more cases, but ranging from only little price surpluses to *"…doubling the price, I would have a hard time with that.*" (IP21). In this context, the interviewees stressed the importance of paying at most a modest premium for green gas.

Another factor influencing the thinking of the interviewees is the role biomethane can play in protecting the environment and mitigating climate change. Again, approximately three-quarters of the interviewees consider this important.

Notwithstanding the benefits of biomethane, 15 of the 22 interviewees consider problematic the so-called "food vs. fuel" question – the debate over using arable land to produce biofuels instead of food. However, their thinking may be diffuse and relativized: "*So theoretically I also see this* *problem. Practically, however, I have not yet really dealt with it.*" (IP04). Or the difficult questions raised may be deflected onto other countries: "*I don't think that we have any problems in Germany because of food cultivation and so on. In Germany, we're actually doing pretty well here. In other countries, it looks different again.*" (IP13).

When questioned about regionality, which past studies have identified as an important attribute of other renewables, more than half of the interviewees revealed this as an important variable in their calculus. However, regional preferences broke into two consumer segments: Those preferring a supplier based in their region; and those preferring regional production sites, i.e. biogas plants: *"[…] if I'm already thinking about sourcing biomethane, I'd think it would be cool if it was from here in the region.*" (IP15).

While regionality is considered important, the type of provider (i.e. municipal utility, cooperative or a commercial corporation) emerged as less relevant. Nine of the 22 interviewees –five who expressed a preference for regional sources and four others– indicated no preference for a provider type: "*Whether that's a private company or not, or whether that's from the state, from the city, or whatever, I don't really care.*" (IP13). Among the interviewees expressing a preference were five for municipal utilities; three for cooperatives; and three for established (and accordingly reliable) suppliers.

Querying interviewees about the opportunity to produce SNG from surplus electricity and CO_2 taken from biogas plants solicited clearly favorable responses: More than three-quarters of the IPs expressed a generally positive attitude towards this form of energy production. It was considered an improvement over regular biomethane, however seven interviewees stressed the importance of using surplus electricity which would otherwise be "wasted": "*So as I said, I'm immediately more interested in it when I say, okay, there's too much electricity, you can use it for something like that, and so it's easier to produce heating energy. I think that's good.*" (IP08). Among the interviewees, there was only one resolute opponent. This aversion was based on efficiency losses in the process, costs caused thereby and a clear preference for a more direct form of electricity storage: "*I'd rather look for a reasonable storage for the surplus electricity, so that I have power at night. […] I mean, I'm taking another step that's costing money. […] The electrical energy must be stored.*" (IP10).

If anything emerges with clarity regarding renewable gas and the related consumer perceptions, preferences and reservations, it is that consumer thinking is complex, sometimes contradictory. Consumers say they are familiar with biogas and biomethane, but familiarity is not knowledge. Their evaluations reveal contradictions: On the one hand, transforming waste materials into energy while mitigating climate change is valued. But if done on a large scale, as would be needed to replace natural gas in the residential heating market, then biogas and biomethane production are regarded negatively. Since PtG technology is largely unknown, it receives a neutral evaluation; however, the idea of generating a green heating fuel from surplus green electricity receives an overwhelmingly positive evaluation.

3.3.3 External view of biomethane and SNG experts on consumers

How do those engaged in the natural gas and biomethane industry perceive the demand side of the residential heating market? Our experts stress that the biomethane segment is a marginal market dominated by a committed segment of resolute green users. One expert pointed out the problem of not being able to practice conspicuous consumption with gas: "*[…] I think the group of people of conviction is small, because heating is just something totally un-erotic. So you drive your electric car and show it off. But you can't show off biomethane in the heating system."* (EX3).

The experts did recognize what our consumer group shows, consumers are cost oriented: "*But ultimately, it all comes down to price.*" (EX1). One common argument used to explain this price sensitivity is 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. So they carry that expectation to renewable heating fuels. A renewable gas product is then rated unfavorably through comparison to the cheaper product from fossil sources. As potential solutions, two ideas were prompted: "*This means that either there is a legal requirement or there is a CO_2 price. Otherwise it won't work.*" (EX3).

The experts also brought up the "food vs. fuel" debate. It is recognized that biomethane suffers through association and that consumers strongly prefer biomethane from waste over gas from energy crops. The experts identified lack of knowledge and confusion as a barrier to adoption. Consumers are said to be unable to differentiate between different gas products, which impacts the marketing and communication strategies of suppliers: "*It is also very, very difficult for these people to understand the product in detail. They simply talk about biomethane. But it's so opaque right now, this eco-gas market, these eco-gas products. Because some [providers] plant trees somewhere and so on. And that's difficult for the end consumer to understand what he's actually getting there.*" (FG2).

This comment highlights the importance of trustworthiness to a consumer who has to navigate competing claims and priorities. Establishing trustworthiness is thought to be achievable through independent certification and labeling. Another (and new) way that came up for establishing credibility with the consumer is a complete proof of origin, now made possible through digital tracing like blockchain technology.: *"[…] so if you then manage to perhaps also establish this plant reference, that you say, okay, this [gas] now comes from this or that plant […]*" (EX2).

Expert assessments of the demand side of the biomethane market tracked well against what our interview partners told us. Expert perceptions of SNG were largely extensions of their perceptions of biomethane. They expect the private consumer market to be small, cost-driven, accustomed to low-price options, and confused about eco-gas. It is thought that certificates of origin would help develop the market. But the most important benefit of SNG over biomethane is seen in greater consumer acceptance, especially given that no energy crops are used: "*So I guess the acceptance of* *this SNG would be high, because even with the worst thinking there is no food vs. fuel et cetera.*" (EX3). However, the word "guess" here speaks volumes, as it points to the almost complete lack of experience among the expert groups in developing and marketing SNG products. Results have to be put in perspective against that background.

3.3.4 Result overview

Table 3-1 summarizes the key findings to our three research questions.

Table 3-1: Summary of key findings

RQ	Content	Key findings
1	Factors driving consumers´ decisions for a specific heating tariff	Choosing a heating tariff can be considered as a low-involvement decision that is driven by cost considerations, indifference and unawareness. For some of the interviewees, the energy provider plays a greater role than the product offered in their calculus.
2	Consumers´ perceptions, preferences and reservations with regard to methane from different renewable sources	*Biogas and biomethane:* Are rather well known, but evaluation is complex and diverse. Large-scale biogas and biomethane production is judged negatively. Still, benefits regarding environmental and climate protection are judged positively. *PtG and SNG:* Are rather unknown and evaluated neutrally. The possibility of generating a usable energy carrier for heating from surplus electricity is evaluated overwhelmingly positive.
3	External view of biomethane and SNG experts on consumers	Voluntary market for biomethane and SNG is considered small, cost-driven and dominated by consumers accustomed to other (low-price) energy products or confused by other eco-gas options, an accurate consumer impression. SNG as well as certificates of origin for individualized products are considered as beneficial for approaching consumers.

3.4 Discussion and conclusions

We conducted a qualitative study to better understand consumer interactions with renewable gas technologies in the residential heating market. Our results – combining the demand-side perceptions and preferences expressed in interviews with 22 individual heating consumers with the expert-perceptions of the demand side surfaced in expert interviews and focus groups with 27 industry experts – reveal a complex and nuanced picture.

To begin, we highlight three circumstances under which decisions for a heating tariff and evaluations of tariff options are made:

1) As is the case with electricity, using an energy tariff for home heating happens for the most part silently and invisibly.
2) Unless consumers decide to change their tariff on a regular (mostly yearly) basis, the tariff decision is not recurring (compared to, say, recycling habits).
3) As shown in our results, opting for a heating tariff is often done based on a specific brand/supplier, either through habit or regionality.

3.4.1 Limits of sustainable consumption theory

Given this decision-making context, a theoretical framework for discussing our results needs to fulfill several requirements: First, it has to offer approaches to explain environmentally friendly and sustainable consumer decisions. Second, it has to include factors that relate to technology use. Third, it should not ignore contextual factors and habitual behavior. Fourth, it should consider the low-involvement of consumers.

Models from the field of social psychology like the VBNM (Stern, 2000), the NAM (Schwartz, 1977) and the TPB (Ajzen, 1991) concentrate on intra-personal factors like values and attitudes as well as inter-personal factors like norms. Models dealing with technology acceptance like the Technology Acceptance Model (TAM) (Davis et al., 1989) or the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003, 2012) tend to have a similar focus and often stem from a work context in which the employer confronts employees with a new technology. In other words, access to the technology is not a construct that is explained in most of these models. Theories of social practice (Warde, 2005; Welch & Warde, 2015), on the other hand, stress the importance of contextual factors like infrastructure and state-led incentives and the role of habits. Moreover, they focus on a practice and not on the moment of acquiring products and services required for participating in the practice. There are integrative approaches to consumer behavior like the MOAM (Blumberg & Pringle, 1982; Ölander & Thøgersen, 1995) or Triandis' (1977) Theory of Interpersonal Behavior that combine intra-personal as well as contextual and habitual factors. However they also focus on recurring behavior and do not take into account the important role of brands/providers as indicated in our interviews and also laid out by Hartmann and Apaolaza-Ibáñez (2012). Moreover, they often assume that consumers invest time and effort to make a conscious decision.

But for most consumers, this is simply not the case when choosing a heating tariff. Given these limits and foci of existing frameworks in sustainable consumption theory, we decided to frame our results from a perspective that we deem central when looking at private commodity consumption: the involvement of consumers.

3.4.2 Low- and high-involvement

Why do we think that the involvement perspective is a promising one for our results? First, results from both consumer and expert interviews from our point of view suggest this perspective:

Consumers often showed little interest and knowledge on gas products, even those who are subscribed to a biomethane tariff. This indifference is highlighted in the following quote "*I pay the bill, I don't care where it comes from.*" (IP18). Moreover, consumers were clearly focused on price. This is reflected in a quote from the expert interviews: *"[…] I think the group of people of conviction [those would be consumers showing a high involvement] is small, because heating is just something totally un-erotic. So you drive your electric car and show it off. But you can't show off biomethane in the heating system.*" (EX3). Second, involvement is a fruitful perspective from which recommendations for marketing can be derived as we will discuss below.

Involvement can be split into two sub-categories: product involvement and purchase involvement. The first is more long-term and related to a product category in general; the second is more short-term and related to a specific purchasing decision (Mittal, 1989; Tzeng & Shiu, 2020). "Product involvement can be summarized as the general level of interest one has in a product, the relevance someone gives to make the right choice or simply the time spent making a decision." (Hanimann et al., 2015, p. 13).

Involvement is influenced by several factors: first, the values, motives and interests of the consumer who makes the purchasing decision. Second, by attributes of the product, such as the price, purchase and use frequency and the type of product (hedonic/functional). And third, by the visibility of the purchase or use of the product (Rahman, 2018).

Product involvement has been found to be important in various ways. First, it means consumers have greater a priori knowledge of the product (Rahman, 2018; Tzeng & Shiu, 2020) and invest more time into searching for information and evaluating a product before buying it; in contrast, consumers rely on easily available cues for low involvement products (Rahman, 2018). Second, product involvement increases trust (Tzeng & Shiu, 2020). Third, and very important for our study, high product involvement enables identity signaling as a symbolic motive for using renewable energy which can increase the use of a green energy product and reduce the price sensitivity (Hanimann et al., 2015).

In energy use, consumers display both low-involvement behavior – such as choosing a fuel with an elevated biofuel content at the gas station or (renewable) energy use in the household – and high-involvement behavior, such as buying an electric car, replacing the domestic heating system or buying an energy-efficient home sensitivity (Foti & Devine, 2019; Hanimann et al., 2015; Jansson et al., 2011).

Our interviewees often showed low-involvement behavior in the selection of a heating tariff. Especially surprising was the fact that even the four interviewees who already had a biomethane tariff or eco-tariff were unsure of what they had actually bought. Our experts offered an explanation for the low-involvement by pointing out that, in contrast to an electric vehicle, consumers cannot show a biomethane tariff to others. This lack of visibility of the purchase and use of biomethane ties in with the literature on product involvement and with consumer research on pro-environmental products. Visibility increases involvement while high involvement drives identity relevance and the ensuing desire to express this identity to others, i.e. more visibility.

We see that involvement emerges through the interaction of a person or group of persons with a product, service or behavior. It is, therefore, malleable and can be influenced, e.g. through the marketing activities of energy producers. If companies succeed at creating high product involvement, they can benefit from a positive effect on consumer choice. With green electricity, Hanimann et al. in their study of Swedish consumers found that "…identity signaling can influence consumer choices and increase demand for renewable electricity." (Hanimann et al., 2015, p. 18). Also Hartmann and Apaolaza-Ibáñez (2012) mentioned self-expressive benefits for renewable energy and Herbes and Ramme (2014) also discussed conspicuous consumption in the market for green electricity. While these results from the green electricity market show how giving consumers the opportunity for identity signaling can be used even for a low-involvement product, we cannot be sure if it works the same way for renewable gas.

3.4.3 *Implications for energy providers*

Let us assume involvement and visibility would help with the selling of green energy. The intangible nature of the products – gas and electricity – still make it difficult to increase visibility and offer consumers an opportunity to express their identity. Green fuels are mostly consumed at home imperceptibly. This is why previous research has repeatedly criticized the lack of opportunity for consumers in the energy sector to signal their identity or practice conspicuous consumption. But practical suggestions for increasing visibility have been scarce and not very inspiring. Hanimann et al. report the limited effect of branded welcome gifts for electricity customers and their respondents suggested "doorplates, stickers, umbrellas or social media applications." (Hanimann et al., 2015, p. 18).

While utilities in the study of Hanimann et al. expressed an interest in enabling consumer signaling and provided support to do so (Hanimann et al., 2015), an extensive analysis from about the same time of the online marketing by more than 600 German utilities found not one mention of any form of identity signaling on a provider website (Herbes & Ramme, 2014). This gap in energy marketing revealed by research finds a parallel in the opinion of our experts that low usage visibility is a barrier for marketing and adoption of renewables.

One promising alternative for marketers could be to complement their (hitherto limited) efforts to engage consumer identity through giving them visible objects such as doorplates or stickers with an approach enabling consumers to express their identity through storytelling.

Storytelling has been examined with regard to sustainability-promoting interventions (Reinermann et al., 2014), sustainable development projects (Bell & Morse, 2007; Lowery et al., 2020; Sparre & Boje, 2020), companies' eco innovation (Hagen, 2008), sustainability reporting

(Jones & Comfort, 2018) and pro-environmental products such as organic food (Nie et al., 2017). An entire Energy Research & Social Science volume (31) was devoted to its application across the energy landscape. Still, its application by companies in their marketing to the energy sector has been largely neglected, the study by Benites-Lazaro on the Brazilian sugarcane industry's strategic use of storytelling being a notable exception (Benites-Lazaro et al., 2017).

Biomethane or SNG products lend themselves especially well to the various genres examined in the context of energy policy storytelling (Janda & Topouzi, 2015). Foremost is the 'hero' story, in which an individual, here a company, helps to fight climate change. This genre could be used by small municipal utilities and energy cooperatives to position engagement with their products as not only contributing to the fight against global warming but also to the fight against stodgy corporate energy incumbents (Herbes et al., 2021b). The 'hero' story would also align with the special role of energy providers identified in the interviews: Some interviewees attach more importance to the provider itself than to the actual product. This is associated with attributes like reliability, regionality or trust. German municipal utility WSW from Wuppertal has established a platform on which consumers can not only choose a renewable energy tariff, but also can choose their individual renewable technology mix and even, taking engagement one step further, the renewable power installation from which they want to source their energy (Wuppertaler Stadtwerke, 2022). The power producers, including local farmers who own a biogas plant or local enterprises with a rooftop PV installation, are personalized on the WSW website using stories of how they started producing renewable energy. This offers ample opportunity for consumers to identify with these stories and create their own story expressing their pro-environmental identity.

One aspect needing mention here is the aversion towards large-scale biogas plants we found among our interviewees. This is especially problematic as upgrading biogas to biomethane is currently economically viable only for larger biogas plants (Daniel-Gromke et al., 2019). The solution to this dilemma remains difficult. Mere storytelling may reach its limits here. In her study of Polish biogas plants, though, Chodkowska-Miszczuk (2021) describes the central role of biogas entrepreneurs as mediators to the public. Through embedding their work in the context of the local social structure, these entrepreneurs provide a human face for their businesses. They not only inform the public, but also share with them their convictions and passions. Through plant visits, conversational meetings, and place-based educational events, a biogas plant is transformed from a faceless corporation to a working member of the community (Chodkowska-Miszczuk, 2021).

Still, providers need to cope with a high price sensitivity of consumers, especially when confronted with cheaper "eco-gas" products, which also appear green, and seemingly low natural gas prices (Gielen & Bazilian, 2021; Kolb et al., 2021) in comparison to higher prices for biomethane (Bowe et al., 2018) and even higher (expected) costs for hydrogen and accordingly SNG (Schimmel et al., 2021). To tackle this issue, some of our experts suggested providers include a fixed share of renewable gases to all their customers in all their products. This would dilute the price premium for all customers and could be used explicitly in marketing and storytelling. Given the expected decrease in the prices of biomethane, hydrogen and SNG over the mid- and long-term, some industry representatives (like the World Biogas Association) are already lobbying for a larger-scale quota solution on the European level (World Biogas Association, 2021).

A less coercive solution would be to make a product with a share of renewable gas the default product. This would leave consumers with a choice but would influence their choice architecture in favor of renewable solutions (Chassot et al., 2017; Kaiser et al., 2020).

The above described solutions and implications could be used to approach different consumers in different ways: We have identified consumer segments (i.e. provider-, environment-, status-quo- and price-centered) that can and should be specifically targeted. Provider- and environment-centered consumer, for example, could be approached through different storytelling and stories, while status-quo-centered and price-centered consumers could be approached with fixed renewable shares or default options.

3.4.4 Implications for policy makers

Turning from the perspective of an energy provider to that of a policy maker, what can the state do to support renewable gases? At present, the market for renewable gases is driven by legal requirements; for an overview see Herbes et al. (2021a). This was also pointed out by the industry experts. While this policy ensures a certain demand for renewable gases, state-led support focusing on specific production technologies (e.g. biogas plants using combined heat and power units) has hindered the development of voluntary markets for renewable fuels (Herbes et al., 2021a). But pricing negative externalities could help even the playing field between natural gas and renewables, an aspect also raised by the experts.

Today's fossil fuels are artificially cheap because CO_2 emissions are not priced into the products. Instead of showing up in the tariff paid by a consumer, the environmental costs are borne by society at large, often disproportionately by its poorer members. The effect is an artificially wide price gap between renewables and fossil fuels, presenting consumers with a pricing incentive to continue using fossil fuels, an incentive that works against the urgent policy need to green the residential heating sector. But if emissions were priced into fuel costs to more fairly represent the expenses incurred through use of the fuel, the markets would change. Kolb et al., using a scenario-based approach, demonstrated "…the effectiveness of CO_2-prices in promoting renewable gases but also emphasized that these prices need to increase significantly in order to have a steering effect." (Kolb et al., 2021, p. 15).

To put this into perspective: To reach a relevant share of renewable gases in the gas mix in Germany of 23 % by 2050 Kolb et al. found necessary a CO_2 price of 152 €/tCO_2 in 2050, a price of 304 €/tCO_2 would lead to a share of more than 50 % respectively (Kolb et al., 2021). For comparison:

The National Emissions Trading System in Germany started in 2021 with a price of 25 €/tCO_2 (German Emissions Trading Authority (DEHSt) at the German Environment Agency, 2020).

In a market governed by CO_2 prices, renewable gases would gain in competitiveness through the carbon assessments on fossil gases. The competition between different renewable gas technologies would still be strong, probably stronger as the available market share would be larger as renewables emerged from their niche market. Furthermore, the steep hike in CO_2 prices can manifest in the short-term as existing heating systems wind down their life cycles, while in the long-term, the residential heating sector is expected to rely on more carbon-neutral technologies such as heat pumps and district heating (Wietschel et al., 2021).

3.4.5 Limitations and avenues for further research

The insights offered by our study also come with limitations. First, our analysis focused on Germany. Given its large biogas sector, currently in a state of upheaval, this means our results are not one-to-one in step with other national contexts. However, the existence in other national contexts of similar legislative conditions, consumption trajectories, and heating dependencies means our results can (at least partially) serve informed decision-making beyond the German borders.

Our results are also limited by the relatively small and opportunistic sample used to represent heating consumers. In these interviews, we tried to minimize distortions through careful monitoring of the interviewee population and adaptation of our sample to maintain a degree of fairness in the heating consumers. Still, our sampling led to a small share of participants from Eastern Germany and a large share of teachers -the latter potentially stemming from snowball sampling. Furthermore, the results are only applicable to people with the actual decision-making power over their heating tariff. We assume this to be closely related to the decision-making power over the heating system, which is strongly correlated to ownership. However, there are also cases (e.g. IP05) who rent entire buildings and can therefore decide on provider and tariff.

A further limitation relates to information provided during the interviews. Following Jones et al. (2017), the technologies under review were framed as ‘green’ and environmental benefits were discussed. Yet our results document low technology awareness among the interviewees, so our providing of information might have influenced the general framing of biomethane and SNG, perhaps even induced a positive attitude towards renewable gas technology. This is especially relevant as previous research (forsa, 2012; Herbes et al., 2018a) has found strongly critical attitudes against biomethane that were spurred on by the “food vs. fuel” debate. However, given the dialogic nature of our interviews, interviewees had ample opportunity to raise critical and negative voices. This openness was also enforced through specific inquiries in the interview guidelines. So we feel the more positive attitude might represent a real change.

This positive turn in public perception of biogas/biomethane appearing in our interviews calls for more detailed study of potential changes in the public discourse, the role of time (habituation), and also the role of legal interventions like the maize cap (Herbes et al., 2014). Furthermore, given the particularities under which decisions in the heating market are made, many approaches and frameworks to explain different components and facets of these decisions have been put forth. Yet no coherent (theoretical) framework exists that takes into account the aspects of sustainable energy consumption in the residential sector.

We see great potential for further research using other framings (e.g. focusing more on cost-related aspects), other national contexts, larger samples or explicitly focusing on different consumer segments. Our qualitative insights can and should be supplemented, validated and expanded through studies measuring preferences, willingness-to-pay and other aspects in the heating market in larger surveys with quantitative methods.

Last, we would like to point out that our study was carried out before the war in Ukraine, which strongly affected European economies, energy markets, inflation and energy prices. These are all aspects which directly and indirectly affect the biogas industry as well as consumers and potentially also their evaluation of alternative heating fuels and the range to which price surpluses are accepted. Further studies could explicitly focus on these effects, e.g. applying a repetitive study on the same topic.

We believe that our study, despite its limitations, provides important insights into consumer decision making in the heating market. The specific focus on renewable gases is especially relevant given their short-term relevance for greening the residential sector. Our results can inform provider as well as political decision-making to support the development of voluntary renewable energy markets.

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

Research article, published together with Peter Kurz and Carsten Herbes in Energy Policy 2024, https://doi.org/10.1016/j.enpol.2023.113857

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.

4.1 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 Commission, 2021b; European Parliament and Council, 2018). 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 & 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 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 (European Biogas Association, 2020; Scarlat et al., 2018). 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 (Gätsch et al., 2022; Götz et al., 2016; Horschig et al., 2018; Ueckerdt et al., 2021; Winquist et al., 2021). 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; Gätsch et al., 2022; Ueckerdt et al., 2021; Winquist et al., 2021). 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 (Herbes et al., 2021; Scarlat et al., 2018). 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 (Götz et al., 2016; Horschig et al., 2018; Scarlat et al., 2018; Winquist et al., 2021). 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 (Danne et al., 2021; Wang et al., 2019), 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 & 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.

4.2 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.

4.2.1 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 (Aruga et al., 2021; Kanberger & Ziegler, 2023; Moon et al., 2023; Narjes & Lippert, 2016; Odland et al., 2023; Ščasný et al., 2017; Walter 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 (Boeri & Longo, 2017; Borriello et al., 2021; Danne et al., 2021; Kalkbrenner et al., 2017; Knoefel et al., 2018; Rommel et al., 2016; Tabi et al., 2014). DCE research related to renewable gases is scarcer, used to analyze farmers' decisions about investing in biogas (Zemo & 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 (Dahlin et al., 2016, 2019; Herbes et al., 2020a). 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.

4.2.2 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 & 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. (2015), Herbes et al. (2016), Kim et al. (2019), Kim et al. (2020), Kowalska-Pyzalska (2019), Oerlemans et al. (2016) and Sagebiel et al. (2014). From this, we identified the relevant product attributes and their levels displayed in Table 4-1.

Table 4-1: 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 C1 (Appendix)*

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 C1 (see Appendix) summarizes these combinations.[5]

(Eco) labels, the second attribute, have been shown relevant for consumer decisions in the energy sector (see e.g. Herbes et al. (2020b), Knoefel et al. (2018), 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 C2. 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 (Fait et al., 2022; Kalkbrenner et al., 2017; Knoefel et al., 2018; Kuhn et al., 2022; Tabi et al., 2014). 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 (Dobers, 2019; Herbes et al., 2018a, 2021; Schumacher & 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

[5] 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.

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 C3 (Appendix). 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.

Figure 4-1 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.

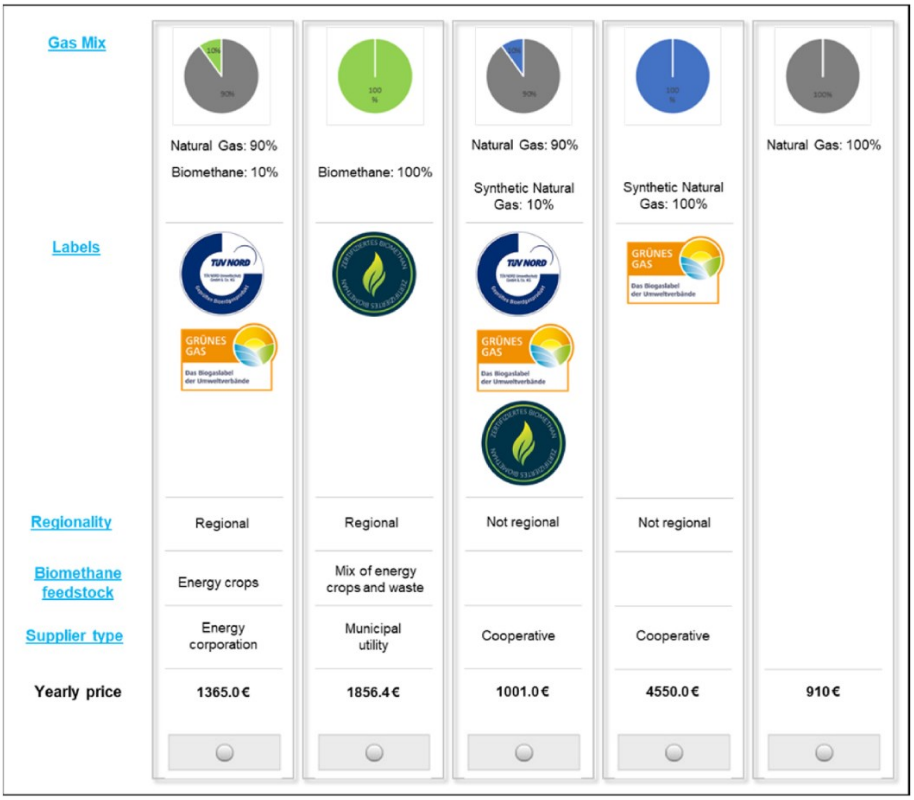

Figure 4-1: Exemplary choice set (translated from German and visualized by authors)

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.

4.2.3 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 (Forsa, 2012; Herbes et al., 2018a), 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 & 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.

4.2.4 *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).

4.2.5 *Sociodemographic variables*

To further guide our analysis, we captured the sociodemographic variables presented in Table 4-2, 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 & Herbes, 2017), invisible consumption (Herbes & Ramme, 2014) and complex, sometimes confusing tariff offerings (Fait et al., 2022; Rilling & Herbes, 2022).

Table 4-2: 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%*	*N/A*	

4.3 Results

Reviewing the residential heating context of our respondents and their knowledge regarding the two underlying technologies, Table C4 (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.

Figure 4-2 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.

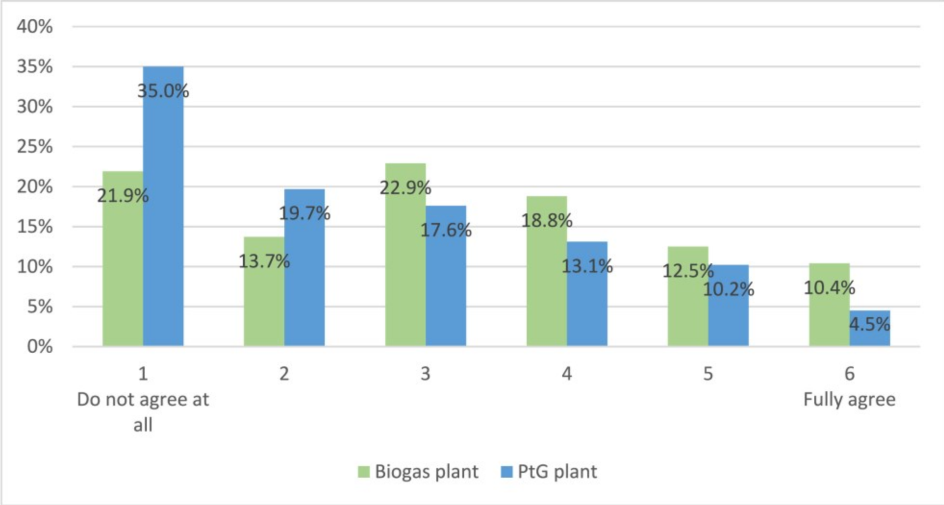

Figure 4-2: Self-assessed knowledge about the functionality of a biogas and PtG plant in the heating market (‘I know how a biogas/PtG plant works’; n = 512)

4.3.1 Hierarchical Bayes estimation: mean utility values and attribute importance

Table 4-3 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 (Côté et al., 2022; Sawtooth Software, 2021a).

Table 4-3: Mean utility values from the HB model, Standard Deviations (SD) in brackets

Attributes	*Level*	*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*

**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.*

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 4-4 displays the according results:

Table 4-4: Attribute importance scores

Attributes	***Importance Scores***
Gas Mix	*33.5 %*
Labels	*16.1 %*
Regionality	*5.1 %*
Biomethane Feedstock	*13.5 %*
Supplier Type	*6.3 %*
Yearly Price	*25.5 %*

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.

4.3.2 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. Dahlin et al., 2016; Sawtooth Software, 2021b; Tabi et al., 2014). 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 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 4-5 shows the average utility values segmented in the two different ways.

Table 4-5: Mean utility values from the HB model for consumer segments

		Knowledge biomethane		*Renewable electricity at home*	
		Unknown	*Known*	*No purchase*	*Purchase*
Attribute	*Attribute levels* **n:**	*289*	*223*	*295*	*217*
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*

**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.*

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 C5 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 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 4-6. 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.

Table 4-6: Attribute importance scores of consumer segments

Attributes	***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 %*

4.4 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.

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 C3 (see Appendix) 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 & 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 & 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.

4.5 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.

4.5.1 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 (Bai et al., 2023; Rilling & Herbes, 2022). 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.

4.5.2 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 (Draper et al., 2013; Li & van 't Veld, 2015), 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.

4.5.3 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.

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5) 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.

5.1 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 (Tosun, 2023). 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 (European

Commission, 2021). For home heating, the fuel of choice for decades in many European countries has been natural gas (Eurostat, 2023), 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) (Joint Research Centre, 2023).

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) (Bundesministerium für Wirtschaft und Klimaschutz, 2022; Geschäftsstelle Expertenrat für Klimafragen, 2023a). According to the latest analyses (Geschäftsstelle Expertenrat für Klimafragen, 2023b; Harthan et al., 2023), 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 (Kern et al., 2023).

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., Hongyang et al. (2022), Huang et al. (2021) and Jovović et al. (2023)) and the installation of new heating systems (see, e.g., Côté et al. (2023), Meles et al. (2022) and Schleich et al. (2021)) 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 (Rilling & Herbes, 2022). 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 (Kolb et al., 2021a).

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

(Kolb et al., 2021a). In Germany, for example, there were 9.876 biogas plants with an installed electric capacity of 5.895 MW in 2022 (Fachverband Biogas, 2023). The biogas produced can be purified into biomethane, which is a direct substitute for natural gas and can be used in the existing infrastructure (Kolb et al., 2021b). In Germany, 242 biogas plants with biomethane injection were in operation in 2022 (Fachverband Biogas, 2023).

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 Horschig et al. (2018), Lauer et al. (2023), Schmid et al. (2019) and Thrän et al. (2023)) 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 (Kolb et al., 2021a; Marocco et al., 2023). 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 (Kolb et al., 2021b; Vega Puga et al., 2022; Winquist et al., 2021). 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 (Rilling & Herbes, 2022) 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 (Rilling et al., 2024) 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 (Jordan et al., 2023). Kim et al. reported that South Korean households would accept a 5% price premium for renewable heat over fossil heat regardless of the renewable source (Kim et al., 2019). Another study from South Korea revealed a 32% willingness to pay (WTP) for renewable heat based on biomethane (Kim et al., 2020). 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 (Bai et al., 2023). 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 (Kim et al., 2022), these studies can still inform and guide the analyses in this paper. Given the lack of existing research focusing 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 (Kern et al., 2023), 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 (Kim et al., 2020) but not yet realized empirically.

5.2 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.

5.2.1 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 (Adamowicz et al., 1994). 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" (Tabi et al., 2014). 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 (Adamowicz et al., 1994).

When DCEs were first introduced, it was only possible to evaluate these experiments on an aggregate level (Louviere & Woodworth, 1983), 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 (Allenby et al., 1995; Allenby & Ginter, 1995; Lenk et al., 1996), even if there is little data for each respondent (Herbes et al., 2020).

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 (Lancaster, 1971). Products and services can therefore be described as bundles of attributes that generate varying utilities for consumers (Lancaster, 1966). Ultimately, consumers strive for maximum utility when making their decision for or against a product (McFadden, 1974; McFadden, 1986). This ties in with the well-established random utility theory. Its basic axiom can be described as (Louviere et al., 2010; Rao, 2014; Train, 2009):

$$U_{in} = V_{in} + \varepsilon_{in}$$

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 (Louviere et al., 2010).

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:

5.2.1.1 Experimental design

Realistic and efficient choice sets are the key to a DCE (Dahlin et al., 2019; Schläpfer & Fischhoff, 2012; Tabi et al., 2014). The importance of "…designing surveys, so that they represent real choice situations as closely as possible" (Tabi et al., 2014) 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 (Rilling & Herbes, 2022). It yielded the attributes and levels shown in Table 5-1.

Table 5-1: 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 5-3*

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

Following Herbes et al. (2021), the Gas Mix attribute covered only renewable shares actually available on the biomethane heating market. These were transferred to SNG products. Table 5-2 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 Kim et al. (2020), Knoefel et al. (2018), Rommel et al. (2016) and Sagebiel et al. (2014), and the second uses aggregate and general absolute numbers like monthly or yearly costs (Kaenzig et al., 2013; Kalkbrenner et al., 2017; Sagebiel, 2017; Tabi et al., 2014). 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.

Table 5-2: 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%*

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 (IWU - Institute for Housing and Environment, 2017). Third, using the average gas price (€/kWh) for private households, differentiated according to the different housing types from (BDEW Bundesverband der Energie- und Wasserwirtschaft e. V., 2021), 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 5-3. 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 Herbes et al. (2020)). For biomethane, market prices from Herbes et al. (2021) were used and varied; for SNG, the calculated production costs came from Schröer et al. (2022). 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.

Table 5-3: 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%*

5.2.1.2 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 (Herbes et al., 2020; Schröer & Latacz-Lohmann, 2024). Each respondent had to complete eleven choice sets (see Figure 5-1) 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.

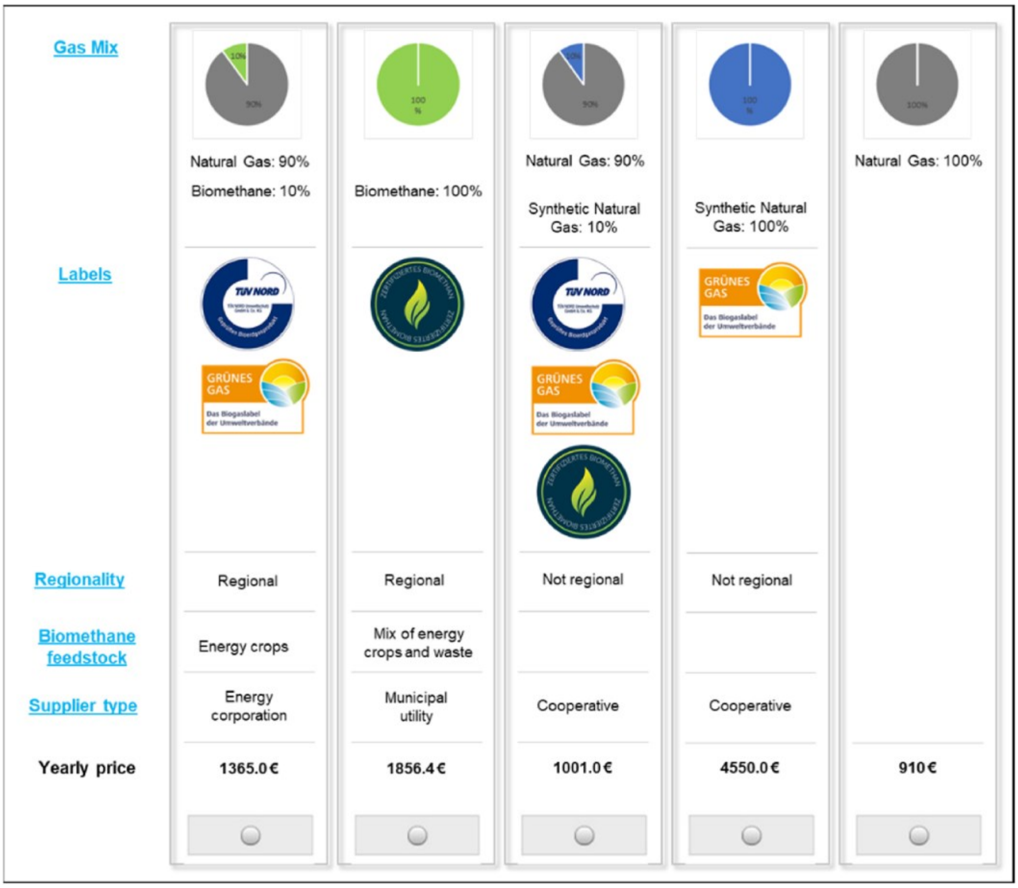

Figure 5-1: Exemplary choice set

Following the procedure described in Herbes et al. (2020) and Rilling et al. (2024), 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 (Goeken et al., 2021). Regression statistics pointed to a reasonably good model fit (Côté et al., 2022; Sawtooth Software, 2023), 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) for completely randomized choices between the five options in every choice set.

5.2.1.3 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 (Herbes et al., 2020; Levy et al., 2004; Wang et al., 2007). 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 5-3). 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 (BDEW Bundesverband der Energie- und Wasserwirtschaft e. V., 2022). 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 (BDEW Bundesverband der Energie- und Wasserwirtschaft e. V., 2022).

5.2.2 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. (2020) 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, 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. (2021) 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. (2022) 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 Schröer et al. (2022), 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 5-4 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.

Table 5-4: Diferent scenario combinations and derived SNG production costs for two alternatives from Schröer et al. (2022)

	SNG alternative 1[a] Combination of a biogas upgrading plant using a membrane process and a raw biogas throughput of 1400 m_n^3/h	***SNG alternative 2***[b] 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 Schröer et al. (2022), the process depicted (SNG alternative 1) yielded the lowest SNG production costs and was 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 Schröer et al. (2022) for this process and are based upon catalytic methanation.

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 Schröer et al. (2022, 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 Schröer et al. (2022) take the estimated costs one step further by adding additional price components that consumers in the heating market have to pay (based upon BDEW Bundesverband der Energie- und Wasserwirtschaft e. V. (2022)):

- Sales costs: 0.4 €ct/kWh
- Grid fee incl. metering and metering point operation: 1.64 €ct/kWh
- 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 (Herbes et al., 2021) 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 BDEW Bundesverband der Energie- und Wasserwirtschaft e. V. (2022)). The combination of these price components allows for calculating end consumer prices that can then be compared to consumer preferences and WTP.

5.2.3 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 (Lancaster, 1966; McFadden, 1974; McFadden, 1986), 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 (Herbes et al., 2020). 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 (Borriello et al., 2021; Danne et al., 2021; Herbes et al., 2015; Kalkbrenner et al., 2017; Rommel et al., 2016). 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. (2017), 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. (2021), 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., Boriello et al. (2021), 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 (Agentur für Erneuerbare Energien, 2022; Rilling & Herbes, 2022). 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. (2015) identified a WTP premium of 15% for a renewable product over a fossil-based one. Kalkbrenner et al. (2017) 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. (2016) 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. (2020) 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." (Rilling & Herbes, 2022). 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 (Böhm et al., 2020; Devaraj et al., 2021; Schröer et al., 2022; Vega Puga et al., 2022). 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.

5.2.4 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 5-5.

Table 5-5: 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*	*Average*	*Sources*
Sex (n = 512)	*Female* *Male* *Diverse*	*39.6%* *60.2%* *0.2%*	*50.7%* *49.3%* *N/A*	*Federal Statistical Office (2023)*
Age (n = 503)	*Mean*	*42.19*	*44.5*	*Federal Statistical Office (2020a)*
Monthly household income (net, n = 512)	*Less than 1000€* *1000-1999€* *2000-2999€* *3000-3999€* *4000-4999* *5000€ and more* *No answer*	*6.4%* *16.2%* *26.2%* *21.3%* *14.5%* *10.2%* *5.3%*	*9.7%* *26.3%* *23.7%* *16.2%* *10.4%* *13.7%* *N/A*	*Federal Statistical Office (2021)*
Construction year of building (n = 512)	*Before 1969* *1969 to 1978* *1979 to 1983* *1984 to 1994* *1995 to 2001* *2002 to 2009* *2010 to 2015* *2016 to 2021*	*24.4%* *11.9%* *10.2%* *12.7%* *17%* *11.3%* *6.8%* *5.7%*	*N/A*	
Refurbishment status (only building built before 2010, n = 448)	*Original condition* *Partial refurbishment* *Conventional refurbishment* *Future-oriented refurbishment*	*26.8%* *43.1%* *21.4%* *8.7%*	*N/A*	
Calculated yearly fuel costs for heating and hot water (€, n = 512)	*Mean*	*845.9*	*820*	*Heiz-spiegel (2022)*
Current gas supplier (n = 512)	*Local basic supplier (municipal utility)* *Another local supplier* *National supplier* *Unknown*	*58.4%* *14.6%* *23.2%* *3.7%*	*64%* *N/A* *36%* *N/A*	*Bundes-netzagentur & Bundes-kartellamt (2022)*

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% (Federal Statistical Office, 2020b). 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 (Schmieder et al., 2023). Almost 60% of the participants have their contracts with Stadtwerke, consistent with the national average (Bundesnetzagentur & Bundeskartellamt, 2022).

5.3 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 Rilling et al. (2024), 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.

5.3.1 Preference shares

Turning to the question posed by the first hypothesis, Figure 5-2 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.

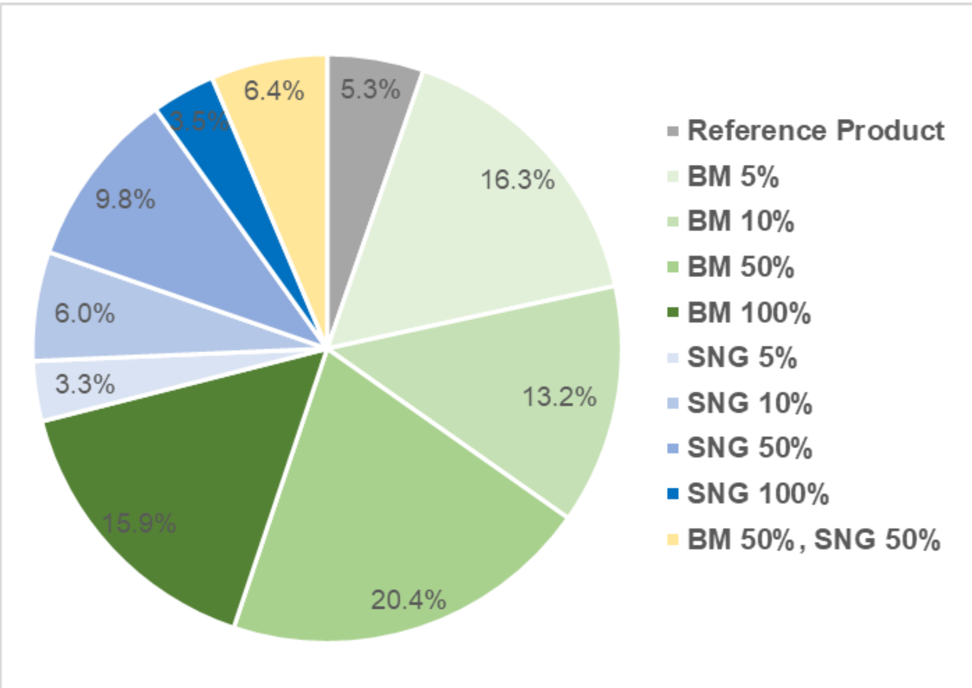

Figure 5-2: Preference Shares for 0% price increase

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.

5.3.2 *Willingness to pay for SNG*

The study's central question about WTP for SNG is addressed by Figure 5-3, which shows the relative WTP over a 100% natural gas reference product:

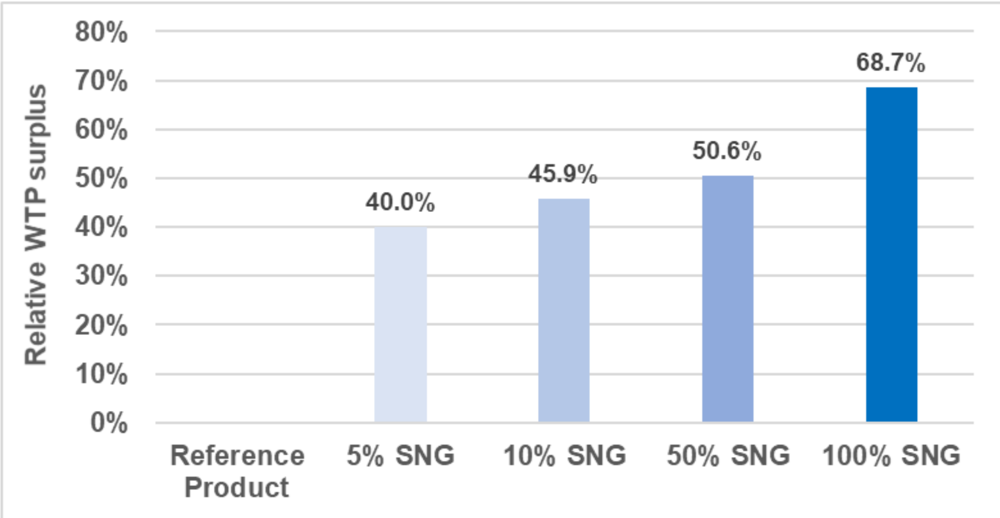

Figure 5-3: Relative WTP surplus for SNG over natural gas

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.

5.3.3 *Matching SNG production costs with WTP*

Do the rising WTP values match rising production costs? Table 5-6 and Table 5-7compare the numbers using two SNG alternatives represented vertically. Table 5-6 presents the *best-case scenario*, and Table 5-7 shows the *normal-case scenario*. A more detailed scenario description can be found in Table 5-4 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 Figure 5-3) by the two end consumer prices for natural gas in the heating market.

Table 5-6: Matching SNG consumer prices to end consumer WTPs 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

Table 5-7: Matching SNG consumer prices to end consumer WTPs 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

Note: Combinations for which WTP exceeds cost are shown in bold

Table 5-6 and Table 5-7 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.

5.4 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.

5.4.1 *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 (Borriello et al., 2021; Danne et al., 2021; Herbes et al., 2015; Kalkbrenner et al., 2017; Rommel et al., 2016). 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 (Rilling & Herbes, 2022) based on interview data from 2020 and thus before the Russian invasion of Ukraine. The shift was confirmed in Agentur für Erneuerbare Energien (2022) 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 5-3). 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.

5.4.2 *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 Schröer et al. (2022). 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 Rilling & Herbes (2022) 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 Rommel et al. (2016), Kalkbrenner et al.

(2017) and Herbes et al. (2015), 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 of a 32% WTP for biomethane- over natural gas-based heat in Korea (Kim et al., 2020). 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.

5.4.3 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 (Green Planet Energy, 2024).

The latest data on gas for the heating market (BDEW Bundesverband der Energie- und Wasserwirtschaft e. V., 2023) 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 (Böhm et al., 2020; Devaraj, 2021; Schröer et al., 2022; Vega Puga et al., 2022), the two markets experience high volatilities that demand close monitoring (Mier, 2023).

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 (Tröndle et al., 2023).

5.4.4 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 (Kröger et al., 2023). 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 (Agentur für Erneuerbare Energien, 2022), 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 Kern et al. (2023)) 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 Schröer et al. (2022)) 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.

5.5 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 (Herbes et al., 2021) 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% (Herbes et al., 2021). 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 (Breer et al., 2023)), and the provision of more centralized heating help to prevent long-term lock-in to fossil and natural gas-based heating (Braunger, 2023). 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 (Götz et al., 2016), 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 (Wachsmuth et al., 2019).

5.6 References

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6) Renewable methane fueling the sustainability transition in private transportation: Identifying consumer preferences through a Discrete-Choice Experiment

Research article

Abstract Renewable gases, such as upgraded biogas (Bio-CNG) or synthetic natural gas (SNG), can contribute to climate change mitigation in the private transport sector. Both emit considerably less CO_2 than fossil Compressed Natural Gas (CNG) and can be used directly in existing infrastructure, i.e., natural gas grids and CNG-fueled vehicles. Motorists and their decisions at the fuel pump are key in this regard. Based upon a Discrete Choice Experiment with 573 German car drivers, preferences for different attributes of renewable gas alternatives were identified. Decision making was primarily driven by the gas mix, prices, and labels. Surprisingly, biomass-based Bio-CNG was clearly favored over SNG from renewable electricity. Furthermore, low price levels and multiple eco-labels were clearly favored. Results suggest that the discourse in Germany, which in the past has been dominated by the "food vs. fuel" debate, has shifted in recent years towards a more favorable view of Bio-CNG.

6.1 Introduction

The transportation sector is a significant driver of the European Union's (EU) greenhouse gas (GHG) emissions. While the overall emissions of the 27 EU member countries have fallen since 1990, those of the transport sector have risen, accounting for more than a quarter of the EU's GHG emissions in 2019. Of these emissions, almost 44% came from private transportation by car, representing the single largest emitter among all modes of transportation, including heavy duty vehicles and civil aviation (European Environment Agency, 2022). This has led policymakers to center their focus on private transportation by car in European and national strategies towards climate neutrality by 2050: "The European Green Deal states that a 90% reduction in GHG emissions from transport with respect to 1990 will be needed by 2050 to achieve climate neutrality in the EU." (European Environment Agency, 2022, p. 27). This is a huge and challenging task, in which the decisions of multiple stakeholders (i.e., policymakers, lobbying associations, entrepreneurs and private motorists) intertwine to influence each other in mutual dependence and require careful balancing.

One intermediate approach towards climate neutrality in private mobility is to replace fossil fuels in existing cars with alternative, less carbon dioxide (CO_2)-intensive fuels from renewable energies (Linzenich et al., 2023). However, the practical application of this approach may give rise to unforeseen difficulties and obstacles: The consequences of a failure to consider different actors and their views emerged with the introduction of E10 in Germany in 2010. With up to 10% biomass-based ethanol blended with regular fuel, E10 was seen by policymakers as a viable step towards reducing carbon emissions. But as Tosun (2017) has documented, the policy-driven rollout led to a boycott by most motorists – despite being known for supporting climate protection measures.

Furthermore, motorists are known to prefer electricity-based fuels over biomass-based fuels (Linzenich et al., 2023). This insight and the disappointing rollout of E10 serve as a cautionary tale motivating this research, particularly as new fuel types are emerging with significant potential to reduce GHG emissions. But that potential evaporates if motorists at the pump do not accept the new fuel. The objective of this paper is therefore to analyze motorists´ preferences for two alternatives for replacing fossil Compressed Natural Gas (CNG) in private transportation in Germany: Upgraded biogas (Bio-CNG) and Synthetic Natural Gas (SNG) from Power-to-Gas (PtG) technology, where green hydrogen from renewable electricity is combined with CO_2 to produce methane. This study therefore ties in with the existing literature on preferences for alternative fuels and adds more in-depth insights with regard to CNG alternatives stemming from biomass and green hydrogen. The results of this study can help fuel retailers in crafting a suitable product portfolio and policy makers in designing efficient and effective policies for the decarbonization of the transport sector.

The remainder of this study is organized as follows: Section 2 reviews the relevant literature on CNG, its renewable alternatives and consumer preferences for renewable fuels; it closes with the study's research questions. Section 3 describes the methodological approach, namely Discrete-Choice-Experiments, and the survey design used in this study. Section 4 provides information on the data collection and the sample; Section 5 presents and discusses the results. Section 6 concludes with the findings of this study, while section 7 surveys avenues for further research.

6.2 Background information and literature review

Researchers have identified multiple approaches to reducing CO_2 emissions from private car mobility including: (1) reduce the need for mobility, e.g., by promoting home office (Wu et al., 2024); (2) reduce travel distances, e.g., through strategic city planning (Krozer, 2017); (3) shift travel to less CO_2-intensive modes of transport like public transportation or cycling (Mocanu et al., 2021); (4) promote more efficient cars, e.g., cars with hybrid engines (McLeay et al., 2018); (5) promote alternative fuel vehicles (AFV) like electric cars (Biresselioglu et al., 2018); and (6) replace fossil fuels with renewable alternatives in existing combustion engines (Linzenich et al., 2023). CNG fueled vehicles offer an interesting case as they fall into the two latter categories: They are considered as AFV (U.S. Department of Energy, 2024) and CNG can be replaced with renewable alternatives.

6.2.1 CNG

CNG fueled vehicles are associated with several advantages over gasoline or diesel fueled vehicles. Burning CNG emits considerable fewer particles, and less carbon monoxide, sulfur dioxide and nitrogen oxide (Khan et al., 2015, 2016). CO_2 emissions from CNG-powered engines have been shown to be 22% lower than diesel (Khan et al., 2015) and 23% lower than gasoline engines (Zukunft Gas e.V., 2023). The number of CNG fueled vehicles has seen steady growth worldwide over the last 20 years, driven especially by demand for light duty vehicles and commercial vehicles in the

Asia-Pacific region (i.e., China, India, Iran, Pakistan) as well as South-America (i.e., Argentina, Brazil, Colombia) (Khan et al., 2015; Savickis et al., 2020).

Europe, in contrast, has seen only low penetration rates of CNG fueled vehicles. In Italy, the largest CNG market in Europe, there are more than 1.1 million CNG passenger cars and vans, representing about 2.5% of all passenger cars and vans (European Commission, 2024). In Germany, the second largest European and in the past slightly growing CNG market, there were approximately 83,000 CNG-fueled passenger cars (plus approximately 18,000 vans) in 2021 (Kraftfahrt-Bundesamt, 2022a). This accounts for a mere 0.19% of all passenger cars (European Commission, 2024).

This is ironic inasmuch as the fuel costs for operating a vehicle in Germany are second lowest for CNG-fueled passenger cars. The following lists €/100 km costs for a range of fuels on the road today (Bundesministerium für Wirtschaft und Klimaschutz, 2024):

- Super gasoline (E5): 10.86€
- Super gasoline (E10): 10.53€
- Diesel: 8.08€
- Liquified Petroleum Gas (LPG): 7.33€
- CNG: 6.69€
- Electricity: 4.84€

CNG's favorable status can (at least partly) be attributed to its tax privileges. Due to CNG's superior CO_2 emission performance, the German Energy Tax Act ("Energiesteuergesetz") granted its production a tax concession (13.90€ instead of 31.80€/MWh) until the end of 2023. However, a gradual phasing out began in January 2024 (Deutscher Bundestag, 2021).

Despite the state's support, manufacturers have not introduced new CNG models, and the number of CNG stations has decreased. This "goodbye" is not without controversy. Both Kramer et al. (2022) and Danieli et al. (2023) point to technical implementation problems that limit market ramp-up of single technologies ("technical bottlenecks" when, e.g., focusing on battery electric vehicles only). They conclude that a mix of technologies, including e-fuels and SNG, is needed to significantly accelerate progress towards climate neutrality in the private transportation sector.

This argument of technology neutrality has also found its way into political discourse, where the initial ban on new vehicles with internal combustion engines in Europe by 2035 is being relaxed. An exemption has been incorporated to permit the registration of new internal combustion engine vehicles beyond the year 2035, as long as they operate solely on fuels that are deemed CO_2-neutral (Automotive News Europe, 2023).

6.2.2 *Renewable alternatives to CNG*

To achieve climate neutrality in CNG fueled vehicles, two approaches or technologies exist: Bio-CNG and SNG. Both gases are chemically equivalent to and functionally interchangeable with natural gas-based CNG. Both emit considerably less CO_2 compared to CNG (European Commission & Joint Research Centre, 2020), but they differ in their means of production.

SNG is based on PtG technology, which utilizes surplus electricity from renewable sources to produce hydrogen in an electrolyzer, thereby enabling the storage of intermittent electricity surpluses. This capability is considered crucial for future energy systems that rely solely on renewable energies; however, the technology has barely begun to gain a market. Total installed electrolysis capacity in Europe grew from a scant 85 MW in 2019 to barely double at 162 MW in 2022. Figures for 2023 range from 191 to 500 MW (European Commission & Joint Research Centre, 2023). SNG is one of the so-called e-fuels, envisioned as a short- to medium-term replacement for natural gas that can cut GHG emissions significantly across a wide range of sectors, including CNG-fueled vehicles (Kolb et al., 2021a; Vega Puga et al., 2022). SNG is produced by methanation, a chemical process whereby the hydrogen produced from electrolysis is combined with CO_2 to produce a synthetic replacement for natural gas. The CO_2 can come, for instance, from a biogas upgrading plant. Audi implemented exactly this process in a pilot plant to produce CO_2-neutral SNG to fuel their CNG vehicle portfolio (Audi, 2013) and was considered a forerunner in this regard; however, in 2021, they sold it to Hy2Gen, a company focused on developing hydrogen projects in Europe (Chemie.de, 2023).

Bio-CNG, as the name implies, is based on biomass. It starts from the anaerobic digestion of different feedstocks like energy crops, organic waste, or manure to produce biogas. This biogas is then cleaned and upgraded to biomethane in a methanation plant (Kolb et al., 2021; Singhal et al., 2017). The resulting biomethane can be injected into the natural gas grid and sold through mass balancing schemes (Bowe, 2013; dena, 2024) into multiple sectors including fuel, where it can be compressed into Bio-CNG.

Using a fossil fuel reference value of 94.1 g CO_{2eq}/MJ, biomethane can reduce emission by almost 91% (Federal Office for Agriculture and Food, 2019). As of 2022, 242 biogas plants with biomethane injection were operating in Germany, providing biomethane for heating, electricity generation and mobility (Fachverband Biogas, 2023; Reinholz & Schmidt, 2023).

Compared to SNG, Bio-CNG can therefore be considered the more mature technology in Germany, having already penetrated the CNG market, where almost 100% of the CNG volume sold in 2022 were Bio-CNG (Reinholz & Schmidt, 2023), and so most of the refueling points sell Bio-CNG. This can be attributed to the political and economic conditions that position Bio-CNG as a means to satisfy EU regulatory requirements. The European directive on the promotion of the use of energy from renewable sources (REDII, European Parliament and Council (2018)) and its implementation through national law, especially the Federal Immission Control Act ("Bundesimmissionsschutzgesetz", Bundesministerium der Justiz & Bundesamt für Justiz (2021)) defines a specific GHG quota. This is a legally prescribed reduction of GHG emissions compared to a "fossil reference value," i.e., the equivalent emissions caused if all fuels sold were fossil-based. This quota increases progressively from 6% in 2020 to 25% in 2030. Those obliged to meet the quota are distributors of fuels, usually mineral oil companies. Distributors who fail to meet their quota face financial steep penalties of 600€ per ton CO_{2eq}.

Fossil-based natural gas cannot fulfill this quota; however, renewable gases such as Bio-CNG and SNG can be used to do so. The eligibility of biomethane for the quota depends on the substrate used, with Bio-CNG produced from manure or sewage sludge classified as an advanced biofuel and therefore clearly favored over Bio-CNG produced from energy crops. So, in addition to direct blending of biofuels, distributors can trade in quotas based on the production of Bio-CNG, giving them another option for reducing their GHG emissions.

Operators of biomethane upgrading plants, i.e., Bio-CNG producers, can sell their GHG quota directly to the obligated companies or via other distributors. This has opened a new and lucrative revenue stream for biomethane operators, serving to explain the high share of Bio-CNG in the CNG market (Güsewell et al., 2021; KTBL, 2023; Naumann et al., 2021; Reinholz & Schmidt, 2023; Reinholz & Völler, 2023; Wagner et al., 2023). This market shift towards Bio-CNG is not seen by drivers of CNG vehicles at the filling station. Despite higher procurement prices in 2022, Bio-CNG remains at favorable prices compared to fossil fuels, as it is offered at the same price as CNG (OG Clean Fuels, 2022; Zukunft Gas e. V., 2024).

6.2.3 Research on consumer preferences for alternative fuels

Current market conditions have meant that CNG drivers in Germany have no real choice of fuel. This, however, neglects their preferences and limits their decision-making scope. In the face of rapidly evolving energy markets, e.g., following the Russian invasion in Ukraine or market ramp-up of hydrogen and e-fuels, insights into consumer preferences for alternative fuels are key for sound political and entrepreneurial decision-making.

Existing research on consumer preferences and decision-making with regard to alternative and more sustainable fuels is dominated by studies on alternative fuel vehicles (Linzenich et al., 2023), for an overview see Ghadikolaei et al. (2021). This focus, however, neglects the specific decision situation. Given the investment amount and the long lifespan of a vehicle, the decision to purchase a green vehicle should be considered high-involvement, comparable a decision for a new domestic heating system (Rilling & Herbes, 2022). Buying a car happens infrequently, and it is usually accompanied by a strategic and lengthy weighing up of options. Buying fuel for an existing vehicle, however, is a regular, recurring decision. It can be considered a low-involvement decision.

Studies on preference for alternative fuels are in comparison much scarcer, CNG-related research is currently absent from the literature. The three closest and therefore most relevant studies - focusing on preferences for alternative fuels (i.e., biofuels and e-fuels) on the German market - are Tosun (2017), Linzenich et al. (2019) and Linzenich et al. (2023). In her analysis of the introduction process of the ethanol-petrol blend E10, Tosun (2017) found that consumers boycotted the bio-based blend back in 2011 for two main reasons: First, concerns about technical compatibility with vehicle engines, i.e., the fear about engine damages caused by this specific fuel. Second, reservations towards bio-based fuels due to competition for arable land, i.e., the "food vs. fuel" debate. This reveals an apparent paradox: Motorists in Germany are known for supporting climate protection measures. Still, they boycotted the introduction of E10 marketed as a more climate-friendly alternative. Tosun also shows the central (yet ambiguous) role of interest groups (like the General German Automobile Club (ADAC)), non-governmental organizations (NGOs) and media outlets during the failed roll-out. Tosun's finding is consistent with that of Linzenich et al. (2023), who found consumers clearly preferring fuels based on renewable electricity over biomass-based fuels. Earlier, in a study based on a stated preference approach (i.e., choice-based conjoint), Linzenich et al. (2019) found fuel prices and availability to be the most relevant decision parameters when deciding for alternative fuels, with consumers largely neglecting pollutant emissions in their decision making.

Insights into consumer preferences for alternative fuels can be supplemented by another market segment where natural gas substitutes, i.e., renewable gases, can play an important role for decarbonization, namely, residential heating. In their qualitative study, Rilling and Herbes (2022) found biomethane to be better known than SNG among heating consumers. In line with Linzenich et al. (2023) and Tosun (2017), they found a critical and negative evaluation of energy crop usage for biomethane production. Still, environmental benefits were evaluated positively. SNG, on the other hand, was widely unknown and evaluated rather neutral.

In a follow-up study based on a Discrete-Choice-Experiment (DCE), Rilling et al. (2024) found consumer knowledge gaps about both SNG and biomethane, which is again in line with Linzenich et al. (2023). Interestingly, and in contrast to Linzenich et al. (2019), price was found to be only the second most important decision parameter after the gas mix, i.e., the share of renewable gases in the tariff. A closer look at the gas mix showed a surprisingly clear preference for biomethane over SNG.

In summary, two opposing empirical findings can be identified. On the one hand, there is research suggesting a preference for electricity-based over biomass-based vehicle fuels; on the other, there are findings suggesting a preference for substituting natural gas with biomass-based alternatives rather than electricity-based in another market, namely residential heating. These insights point towards the need to explore in more detail consumer preferences in another renewable gas market, namely the CNG market. Insights into CNG can inform other fuel segments, where biomass-based and electricity-based fuels are considered. Insights into the German market can also inform decision-making in other countries with developing CNG markets like Italy (European Commission, 2024; Prussi et al., 2021).

Adopting renewable-based CNG alternatives depends on consumer acceptance, preferences, and their willingness to use these alternatives, leading to the study's research questions:

Which attributes of renewable gas products are important to consumers in motorized private transportation, and how important are these attributes?

6.3 Discrete-choice-experiments (DCEs) and survey design

This paper builds on a DCE implemented through an online survey. Utilization of DCEs to assess stated preferences has progressed into a fundamental method in both academic studies and practical applications. The method involves presenting respondents with a set of alternatives, or choice sets, each with different attributes, and asking them to choose the one they prefer. Not surprisingly, DCEs have been widely used in transportation and mobility research (Gundlach et al., 2018; Hackbarth & Madlener, 2013; Khan et al., 2020; Kim et al., 2023; Senkpiel et al., 2021).

DCEs build upon random utility theory, describing the utility consumers derive from different alternatives presented in varying choice sets. It rests on the assumption that from each choice set presented, respondents choose the alternative that provides them the highest utility. Respondent preferences reflect the (implicit) utility derived from each alternative, which researchers try to capture and measure by making explicit. However, not all factors influencing individual decision making can be measured or observed. Accordingly, the utility U that respondent i receives from alternative n is given by $U_{in} = V_{in} + \varepsilon_{in}$ (Rao, 2014), where V is a systematic component that is observable from the DCE design, and ε is a random, unobservable component (Louviere et al., 2010; McFadden, 1974, 1986; Rao, 2014; Train, 2009).

While the tested alternatives can be goods, services or policies (Rilling et al., 2024), all DCEs have in common that alternatives are broken down into different attributes that define each option in a choice set (e.g., price); each attribute can take on specific values, or levels, in a choice set (e.g., €1, €2, €3). Respondents have to decide between different alternatives multiple times. Building on the gathered choice data, preferences can then be calculated through pseudo-individual part-worth utilities for each attribute/level.

Following Rilling et al. (2024), the experimental design for this study builds upon an extensive literature review as well as 23 qualitative interviews. This approach resulted in five attributes and their according levels. Table 6-1 summarizes all attributes and their levels.

Table 6-1: Product attribute and attribute levels

Attribute		Attribute Levels
(1) Gas Mix	***(1.1) Bio-CNG Share***	*100%*
	(1.2) SNG Share	*0%* *5%* *10%* *50%* *100%*
	(1.3) Natural Gas Share	*0%* *50%* *90%* *95%* *100% (Reference Product)*
(2) Eco-Labels		*No label* *TUEV* *GGL* *Fake* *TUEV + GGL* *TUEV + Fake* *GGL + Fake* *TUEV + GGL + Fake*
(3) Regionality/Proximity of production sites		*Not Regional* *Regional*
(5) Bio-CNG Feedstock		*Energy crops* *Waste* *Mix of energy crops and waste*
(6) Price per liter		*Various product-specific price increases (see Table 6-3)*

Table 6-2 summarizes the combinations of renewable shares presented in the alternatives. As discussed in section 2.2, conditions in the German CNG market mean it is almost 100% Bio-CNG (Reinholz & Schmidt, 2023), and so no incremental shares for Bio-CNG were tested. Incremental shares were tested for SNG products, given their significantly higher production costs (Böhm et al., 2020; Devaraj et al., 2021; Schröer et al., 2022; Vega Puga et al., 2022). Shares were either "topped up" with cheaper natural gas or mixed half-and-half with Bio-CNG. A 100% natural gas product was used as reference product.

Table 6-2: Varying shares of different gas sources used in this study

Product	*CNG Share*	*Bio-CNG Share*	*SNG Share*
Reference Product	*100%*	*0%*	*0%*
Bio-CNG: 100%	*0%*	*100%*	*0%*
SNG: 5%	*95%*	*0%*	*5%*
SNG: 10%	*90%*	*0%*	*10%*
SNG: 50%	*50%*	*0%*	*50%*
SNG: 100%	*0%*	*0%*	*100%*
Bio-CNG: 50%, SNG: 50%	*0%*	*50%*	*50%*

As outlined in Rilling et al. (2024), the existing literature shows that labels, regional production, and bio-CNG feedstock are relevant for consumer decision-making, which was also supported by the 23 preliminary interviews.

While not established in the current fuel market, eco-labels have been found highly relevant for renewable electricity and renewable gases in the heating market. Therefore, three alternatives and their combinations were tested. The first two were genuine: the well-established TUEV-label and the stricter Green Gas Label (GGL) awarded by environmental associations. The third was a fake label developed and tested in the DCE. Its inclusion was to account for previously identified knowledge gaps regarding labels in the energy market (Rommel et al., 2016).

Given that some plant operators offer locally produced Bio-CNG, the aspect of regional production (i.e., proximity to the production site) was added as attribute. This choice also appears in other energy-related studies, where findings point to consumer preferences for regional production (Fait et al., 2022; Kalkbrenner et al., 2017).

Given past controversies over fuels based on energy crops (Linzenich et al., 2023; Tosun, 2017), different feedstocks for Bio-CNG were tested: energy crops, waste and a mix of both. Since this is only relevant for Bio-CNG products, the feedstock attribute for SNG products was left blank in the choice sets.

Following other energy-related DCEs (Knoefel et al., 2018; Rommel et al., 2016; Sagebiel et al., 2014), the price attribute was presented using per unit prices, i.e., the equivalent price of one liter E5 gasoline for one kg CNG. Using the equivalent price was done for two reasons. First, it reflects the actual price level of CNG, which is lower compared to gasoline and diesel. Second, given the small size of the CNG market, respondents might not be used to per kg prices. Equivalent prices were based on a reference price of 0.73 €. This price was altered using different price levels, ensuring one common level, i.e., no increase, and five more levels ensuring high enough prices to avoid under coverage: The highest price level should be above the highest willingness-to-pay of respondents. Table 6-3 summarizes the different price levels.

Table 6-3: Price levels used in the DCE (all prices in €)

Price level	***Bio-CNG: 100%***	***SNG: 5%***	***SNG: 10%***	***SNG: 50%***	***SNG: 100%***	***Bio-CNG: 50%, SNG: 50%***	***Reference product***
1	*0.73*	*0.73*	*0.73*	*0.73*	*0.73*	*0.73*	
2	*0.92*	*0.77*	*0.77*	*0.92*	*1.10*	*0.92*	
3	*1.10*	*0.81*	*0.81*	*1.10*	*1.47*	*1.10*	*0.73*
4	*1.47*	*0.86*	*0.88*	*1.83*	*2.93*	*1.47*	
5	*1.83*	*0.88*	*0.98*	*1.99*	*3.25*	*2.15*	
6	*2.20*	*0.92*	*1.11*	*2.63*	*4.52*	*2.59*	

The DCE was further integrated into a survey that systematically examined details on vehicle usage, familiarity with Bio-CNG and SNG, socio-demographic attributes, and opinions regarding diverse financing alternatives for renewable gases.

6.4 Data

The empirical procedure – including experimental design, data collection, and analysis – was conducted together with the market research institute bms marketing research & strategy. Sawtooth software was used to conduct the survey (including the DCE) as well as to analyze the DCE data.

The survey was finalized based upon seven think-aloud pre-tests. To address previously identified knowledge gaps in consumer understanding of renewable gases, especially of SNG (Linzenich et al., 2023; Rilling et al., 2024), a video was produced to explain the underlying technologies. This video can be found here and sets the stage for the decision-making in the DCE as well as for further modeling. Besides providing information on the controversially perceived origin of the different fuels (Linzenich et al., 2023; Tosun, 2017), the video provides information on CO_2 emissions, availability of CNG and Bio-CNG in comparison to regular gas stations as well as the compatibility of SNG and Bio-CNG with today's engines – an important and controversial aspect of the introduction of E10 in Germany (Tosun, 2017). Respondents were obtained through Kantar Profile Networks, which provided a representative sample of the German population. The recruitment of respondents followed the standard procedure of bms, whereby first potential respondents were invited via e-mail to participate in the survey. Those who chose to clicked to an introductory page explaining the thematic focus of the survey, its duration as well as participation incentives. Following this page, respondents were screened according to three eligibility criteria: They had to own a car, be familiar with CNG-fueled cars, and be at least 18 years old.

The average survey completion time, including the video (3:24), was approximately 15 minutes. Soft launch was in May 2021; after preliminary analysis of 182 responses for duration and data quality, the survey period ended on June 10, 2021, with 573 respondents. Participants had to decide between four product alternatives plus the reference product in eleven so called choice sets (see Figure 6-1), yielding a total of 6,303 choices.

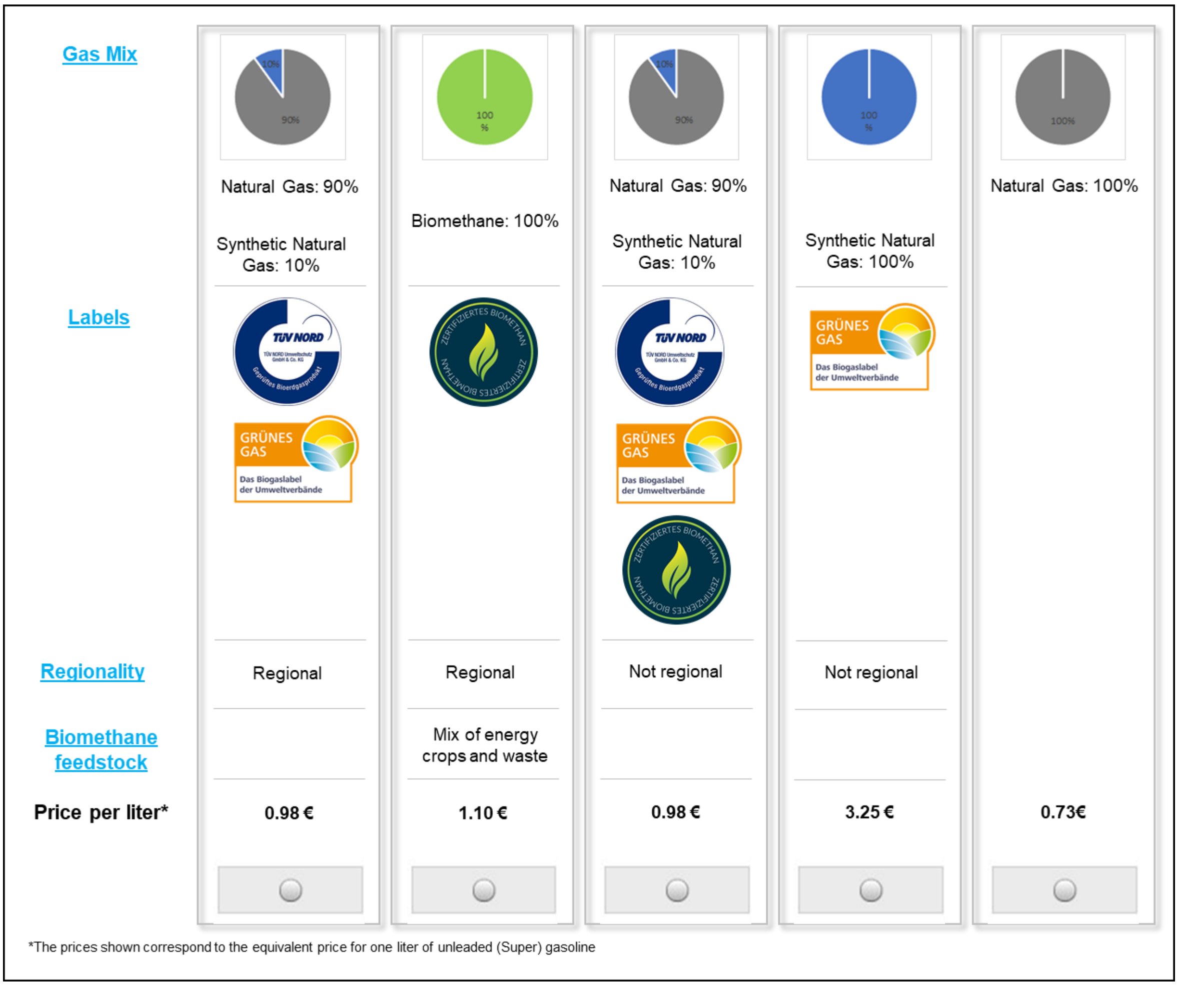

Figure 6-1: Exemplary choice set

Data collected were analyzed through a Hierarchical Bayes (HB) regression model, allowing the calculation of part-worth utilities on a pseudo-individual level (Allenby et al., 1995; Allenby & Ginter, 1995; Lenk et al., 1996). The approach was based on a two-level model. Firstly, a multinomial logit model was utilized to scrutinize the selection of one option over another for each respondent, constituting the lower level. Secondly, the upper level posits that the part-worth utilities adhere to a multivariate normal distribution at the population level. This two-level approach is renowned for its adeptness in capturing preference diversity and deemed state-of-the-art in assessing consumer preferences through DCEs (Goeken et al., 2021).

The model statistics from the HB model reveal insights on how the model fits the data. With a Pseudo R-Squared (Pct. Cert.) of 0.52 and a Root Likelihood of 0.46, which is more than two times greater than the chance level of 0.2 (theoretical value for completely randomized choices between five alternatives), the model performed well (Côté et al., 2022; Hille et al., 2018; Sawtooth Software, 2023).

Table 6-4 summarizes the most important sociodemographic and mobility-related attributes of the respondents in the survey. The table further shows national averages to compare against survey percentages. The survey sample is slightly dominated by wealthier, male respondents and clearly dominated by younger respondents. Looking at car-ownership we find the largest share of respondents driving their own cars, which strengthens survey validity as company-owned cars usually come with free re-fueling and so distort decision-making. With regard to fuel types, we find a higher share of AFV (i.e., electric, hybrid and LPG as well as CNG cars) in the sample compared to the national average. The fact that almost 60% of respondents said they were aware of the possibility of replacing fossil CNG with Bio-CNG is in sharp contrast to Rilling et al. (2024), who found few consumers aware of this possibility in the heating market.

Table 6-4: Socio-demographic and mobility-related information of the sample and comparison to national statistics

Variable	*Values*	*Sample*	*National Average*	*Source*
Sex (n = 573)	*Female*	*42.1%*	*50.7%*	*Federal Statistical Office (2023)*
	Male	*57.4%*	*49.3%*	
	Diverse	*0.5%*	*N/A*	
Age (n = 563)	*Mean*	*34.8*	*44.5*	*Federal Statistical Office (2020)*
Monthly household income (net, n = 512)	*Less than 1000€*	*3.8%*	*9.7%*	*Federal Statistical Office (2021)*
	1000-1999€	*16.6%*	*26.3%*	
	2000-2999€	*23.7%*	*23.7%*	
	3000-3999€	*21.1%*	*16.2%*	
	4000-4999	*13.4%*	*10.4%*	
	5000€ and more	*13.1%*	*13.7%*	
	No answer	*8.2%*	*N/A*	
Private vs. company car (n = 573)	*Private car*	*92.1%*	*N/A*	
	Company car	*7.5%*		
	Others	*0.3%*		
Engine/fuel type (n = 573)	*Gasoline*	*58.1%*	*63.9%*	*(Kraftfahrt-Bundesamt, 2022b)*
	Diesel	*30.7%*	*30.5%*	
	Electric	*3.5%*	*1.3%*	
	Hybrid	*4.2%*	*3.4%*	
	LPG	*2.8%*	*0.7%*	
	CNG	*0.7%*	*0.2%*	
Knowledge about replacing CNG with Bio-CNG (n = 573)	*Known*	*59.3%*	*N/A*	
	Unknown	*40.7%*		

6.5 Results and discussion

Before watching the orientation video to the DCE survey, the 573 respondents were asked to evaluate their understanding of the operations of a biogas and PtG plant. Figure 6-2 shows their self-evaluations (“I know how a biogas/PtG plant works”).

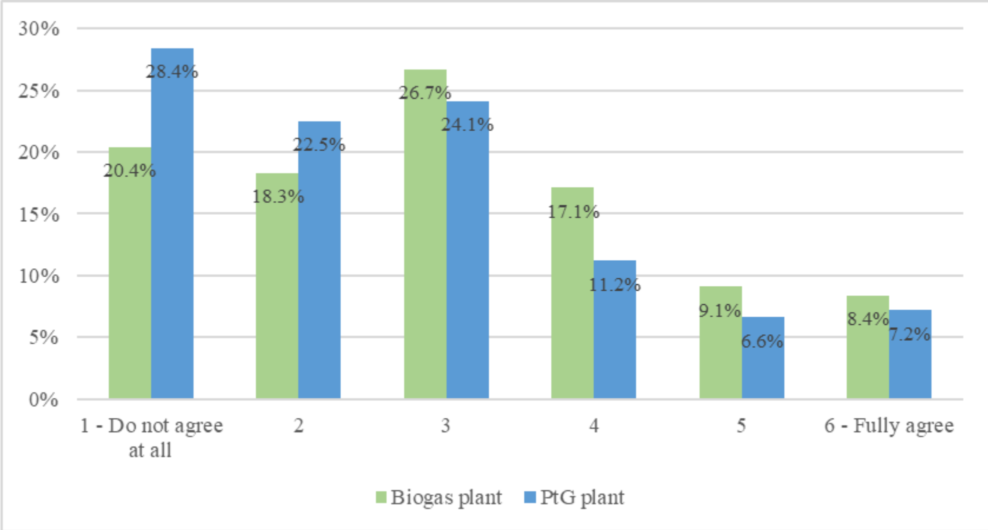

Figure 6-2: Self-assessed knowledge about the functionality of a biogas and PtG plant in the transport market (n = 573)

The results clearly show that respondents recognized knowledge gaps in their understanding of both biogas and SNG/PtG generation. They are slightly more pronounced for the newer PtG technology than for the more established biogas technology and overall, less pronounced than found by Rilling et al. (2024). Still, these results confirm Linzenich et al. (2019, 2023) with regard to gaps in knowledge about alternative fuels.

6.5.1 Preference Shares

The estimation method and the design of the price attribute, where each renewables option was presented at the same price as the reference product, allow the calculation of so-called preference shares. These simulate the preferences of respondents for the alternative products in a market without price differences between products. This situation is unrealistic, but the results can be used to estimate price-independent preferences, as shown in Figure 6-3.

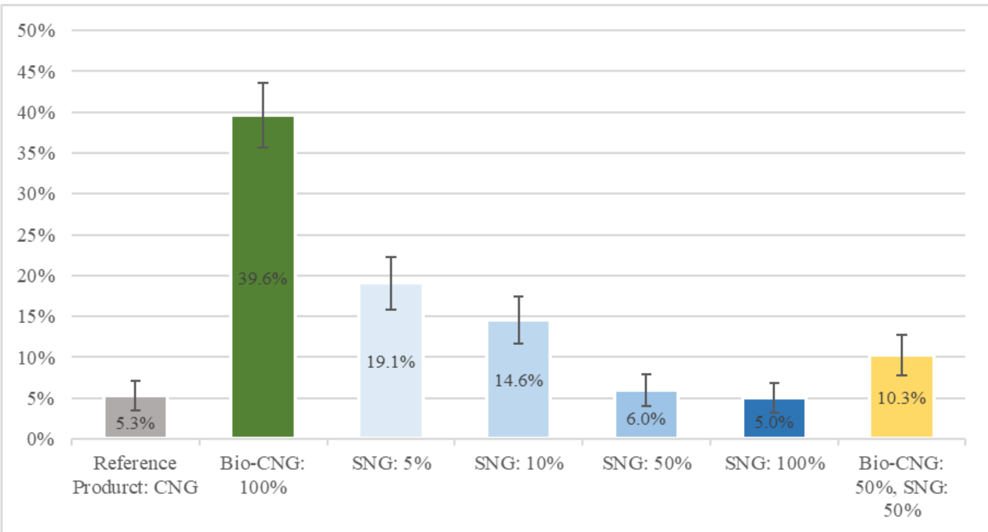

Figure 6-3: Preference Shares for 0% price increase, error bars indicate 95% Confidence Intervals (n = 573)

In this fictional scenario, a small but relevant share of approximately 5% of respondents prefer fossil CNG over its renewable alternatives. Bio-CNG is preferred over any SNG share, preferences for SNG decline with increasing share in the product and in the mix product (i.e., Bio-CNG: 50%, SNG: 50%) Bio-CNG appears to make SNG more attractive. This indicates preferences for the one biomass-based product over four different SNG products – given that all alternatives were shown equally often in the DCE.

6.5.2 *Mean Utility Values*

To gain further insights, the mean and zero-centered part-worth utility values for the different attribute levels were analyzed, with the results shown in Figure 6-4.

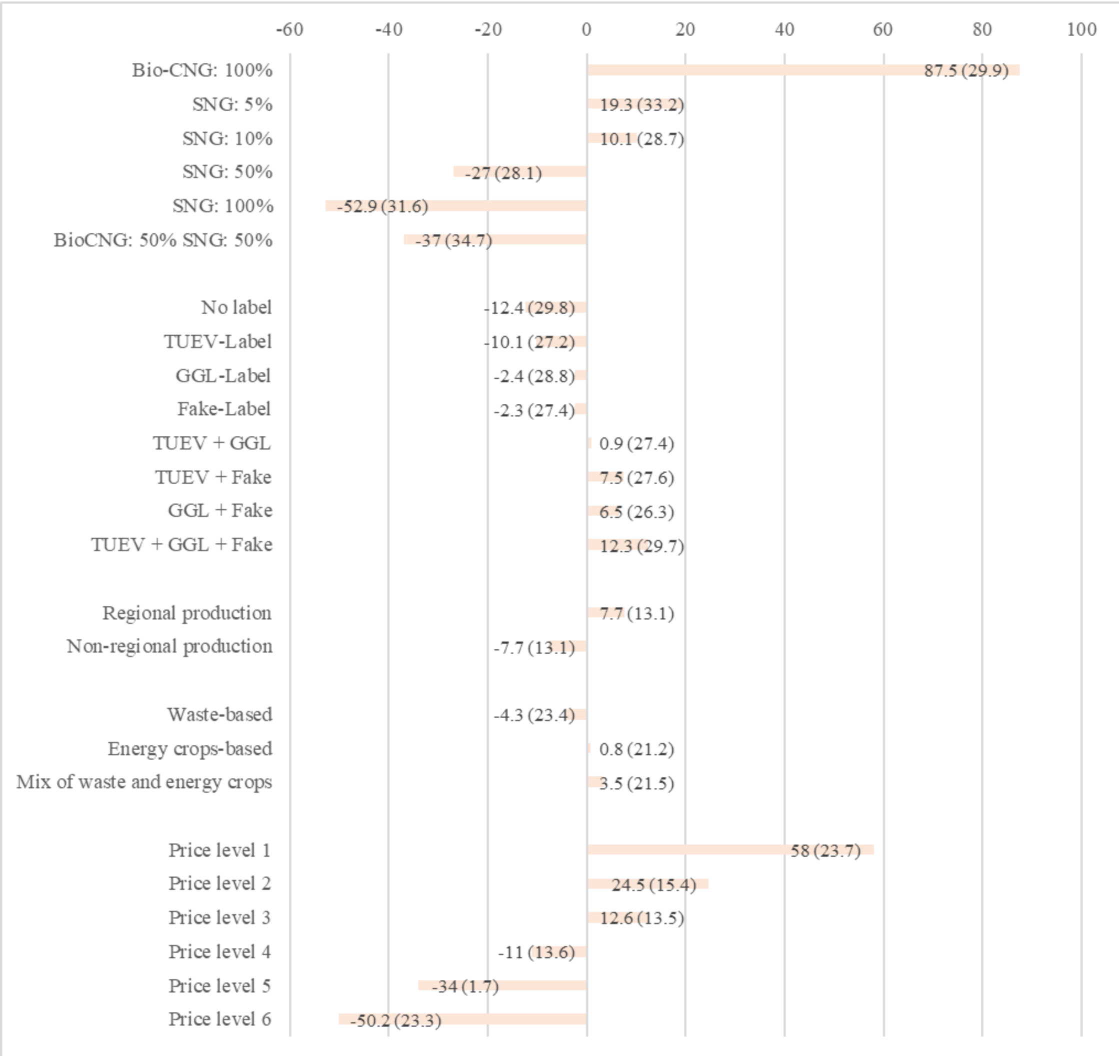

Figure 6-4: Zero-centered mean utility values from the HB mode, standard deviations in brackets (n = 573)

The values can only be compared within one attribute and sum to zero within that attribute. For binary choices, the level with the higher utility value is favored over the other. In instances involving three or more levels (e.g., labels), the level with the highest value is generally preferred, all else being equal (Orme, 2010).

Figure 6-4 clearly shows that Bio-CNG is favored over the other products and lower price levels (levels 1-3) are favored over higher levels. With regard to labels, we see a quantity effect, where products with more labels are clearly favored. So is regional production. Interestingly, the fake label performed best as a single label and boosted the utility value in every combination with the legitimate labels. These results agree with Rilling et al. (2024), who found the same "more, the merrier" effect and confusion caused by the fake label.

Ascribing higher importance to more (partially substitutive) labels also signals insecurity and knowledge gaps with regard to decision making for renewable gases and their labeling. Other studies like Tebbe and Blanckenburg (2018) and Piracci et al. (2024), analyzing established and well-known sustainability labels for food products, did not find a correlation between the number of labels and preferences. The authors explained that one label already signals "sustainability per se", while more labels do not signal additional utility. In the case of renewable gas products, additional labels might serve to mitigate insecurity in decision making for an unknown and/or low-involvement product.

The renewables share preferences found here are contrary to the preferences found by Linzenich et al. (2019, 2023). The DCE clearly revealed a preference for biofuels over the e-fuel SNG, which is contrary to the public and scientific discourse from the past (especially related to the food vs. fuel debate). In this regard, consumers preferring energy crops over waste-based feedstocks for Bio-CNG came as a surprise, as it defies the "food versus fuel" argument that has dominated the public discourse in Germany for a long time. However, more recent studies, e.g., Rilling et al. (2024), on renewable gases in the heating market or Agentur für Erneuerbare Energien (2022) on renewables in general, also found this shift in public perception.

6.5.3 Importance Scores

From the HB-based results, importance scores for different attributes can be calculated from the range of utility values for a given attribute. The relative importance of the attribute is estimated by comparing the range to that of other attributes, the idea being that the greater the range, the greater the impact the respective attribute levels have on a decision. The ranges are normalized to sum to 100% for comparison. With 41.5%, we find the Gas Mix (i.e., the share of renewables in the product) to be the most relevant attribute – again in contrast to Linzenich et al. (2019) who found price to be the most relevant attribute. Price was found second most important in this DCE (21.6%), followed by eco-labels (20.2%). In contrast, regional production (6.3%) and Bio-CNG feedstock (10.3%) were markedly less important.

In essence, the results confirm those of Rilling et al. (2024), based on a similar DCE with an independent sample by the same researchers, but focusing on a different market segment (i.e., residential heating). In both cases, biomass-based fuel is favored over the electricity-based alternative and price is only the second most important attribute. This is in stark contrast to other studies (i.e., Linzenich et al. (2023), Linzenich et al. (2019) and Tosun (2017)) and needs contextualization. First, comparing current market conditions (with almost 100% Bio-CNG offerings) to preferences reveals a good match, in that CNG drivers get what they want – although the supply side is driven by legal obligations, not by consumer preferences (Herbes et al., 2021; Reinholz & Schmidt, 2023). Second, the foci of the papers compared diverge slightly. Tosun (2017) conducted an ex-post analysis of the actual introduction of a (partial) biomass-based alternative to gasoline sold physically at fuel stations (i.e., E10). Building upon a stated preference-approach, Linzenich et al. (2019) looked ex-ante into alternative fuels in general, not taking into account their origin (i.e., electricity- or biomass-based) and actual market availability. Linzenich et al. (2023) used a standard online survey built on multiple constructs to elicit ex-ante beliefs and preferences for alternative fuels in general and their origin (i.e., bio- and e-fuels) in detail. Actual decisions, however, were not considered.

This study builds upon a stated preference approach, focusing on an established biomass-based alternative (i.e., Bio-CNG) and a developing alternative (i.e., SNG). The DCE tests products that are usually not sold physically but via mass balancing schemes and that are partially already available in the market (i.e., Bio-CNG). Bio-CNG's availability in the market plus the identified knowledge gaps about SNG could explain why the biofuel in this DCE was favored over the e-fuel. Consumers seem to prefer what they understand and know better (Bharadwaj et al., 2023). Certainly, the preference for biofuel has also benefited from the general shift of public perception around the "food vs. fuel" debate (Agentur für Erneuerbare Energien, 2022; Rilling et al., 2024).

6.6 Conclusions

Decarbonizing the mobility sector is central to climate change mitigation. Alternative fuels that can be used in existing internal combustion engine vehicles and are based on renewable sources can help achieve this decarbonization in the short to medium term. Based upon a DCE with 573 respondents and accordingly 6,303 active decisions between five product alternatives, this study identified preferences for renewable alternatives (i.e., SNG and Bio-CNG) for fossil CNG on the German market. The guiding research questions were:

Which attributes of renewable gas products are important to consumers in motorized private transportation, and how important are these attributes?

These questions can be answered as follows. Gas mix, i.e., the share of renewable gases, is the most important attribute, followed by price and labels, which are almost equally important. Biomass-based Bio-CNG is clearly favored over SNG, an e-fuel based upon green hydrogen derived from renewable electricity. And lower price levels are preferred over higher. Quantity trumps quality when it comes to eco-labels. More labels were preferred to fewer labels, regardless of the label strictness.

Accordingly, consumer preferences are well reflected in the market supply. Almost all CNG sold is Bio-CNG, the most important and preferred product. With regard to policies, we therefore see the "success" of a measure where emissions are significantly sanctioned through a market-based policy approach, namely the GHG quota. Distributors are taking advantage of a window of opportunity to meet their quota obligations with a slowly declining market segment (i.e., CNG vehicles). On the supply side, operators of biogas and biomethane upgrading plants benefit from high prices at a time when many operators are looking for new business models after the end of a long period of protected and subsidized electricity production with guaranteed feed-in-tariffs (Reinholz & Schmidt, 2023). Furthermore, in the current context, the CNG market is a good example of a low-involvement product in a voluntary market that has been steered by policy towards significantly lower GHG emissions, without any noticeable consumer backlash in contrast to, for example, the failed introduction of E10 in Germany.

However, this finding needs to be put into perspective. Compared to regular gasoline, CNG was and is a niche market. Transferring this to other and larger markets, e.g., residential heating or other fuels, remains challenging. The study results, however, can certainly inform decision-making beyond CNG and with regard to other fuels, i.e., e-fuels in general. First, their origin should be communicated explicitly, potentially combined with information on emission reduction potential. Second, price competitiveness over fossil and bio-based alternatives needs to be ensured. Third, (eco) labels are surprisingly relevant to consumer decision making, although they are not used in the current fuel market. This opens up opportunities for fuel distributors and labeling organization or for concepts of state-run and standardized labeling scheme(s) (Rommel et al., 2016). The perceived utility of the fake label in this study indicates confusion and insecurity among consumers. Fourth, ensuring technical compatibility by explicitly guaranteeing or explaining similar (ideally identical) chemical properties can help avoid the backlash seen with E10.

When crafting policies on bio-based fuels and electricity in the past, lawmakers faced a fierce fuel-versus food debate (Manning et al., 2015; Tosun, 2017) and additionally, a debate about “maizification” of the landscape due to German biogas plants mostly using maize silage as input (Herbes et al., 2014). This has led to policies restricting the use of energy crops. Our results suggest that policy makers today can make their decisions on bio-based fuels without fearing strong adverse public discourse. This opens up additional options in the energy transition.

6.7 Limitations and avenues for further research

The results of this study face some limitations due to the empirical approach taken for this paper. Collecting data through Kantar Profile Networks ensured access to a representative sample, but the selection criteria resulted in a relatively young sample, not necessarily representative of progressively aging car owners (Kraftfahrt-Bundesamt, 2021). Also, the information about the different types of fuels and its presentation in a mandatory video before the survey may have interfered with perceptions. For example, information on different GHG emission reductions for the different technologies were discussed in the video and not added explicitly as an attribute in the DCE. In addition, participants could not continue with the survey while the video was playing; however, given the online setting of the survey we cannot control or guarantee that the video was watched with full attention. The anonymized online setting and stated preference-approach could have led respondents to under-value prices compared to decisions in a real-life setting. The final concern relates to the narrow one-country and one fuel scope: CNG and its alternatives in Germany.

Still this study provides interesting insights, which can be developed and tested further, both empirically and theoretically. Further DCE-based studies could look into bio- and electricity-based alternatives to gasoline/diesel in private transportation and thus enlarge the target population. This would be particularly relevant in light of recent developments regarding the EU internal combustion engine ban, which has been relaxed significantly as a result of political negotiations. This political discourse itself also offers great potential for an in-depth analysis.

Furthermore, future research could expand the CNG-focus to other countries where CNG plays an increasingly important role or to other transport sectors with a higher market potential (e.g., replacing Liquified Natural Gas (LNG) used for heavy duty transport with a biofuel, i.e., Bio-LNG). Given the identified knowledge gaps, studies could also look into how different forms of information presentation influence decision-making and preferences.

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Supplementary material

Appendix A to Policy frameworks and voluntary markets for biomethane – How do different policies influence providers' product strategies?

A1: RHI tariffs

Eligible Technology	Eligible Sizes	Accreditation date	Tariff Rate 2019/20 (p/kWh)	Tier
Biomethane injection	All capacities	before 1 January 2015	8.44	
	First 40,000 MWh	before 1 July 2015	8.44	Tier 1
	Next 40,000 MWh		4.95	Tier 2
	remaining MWh		3.83	Tier 3
	First 40,000 MWh	between 1 July and 30 September 2015	8.03	Tier 1
	Next 40,000 MWh		4.71	Tier 2
	remaining MWh		3.64	Tier 3
	First 40,000 MWh	between 1 October and 31 December 2015	7.24	Tier 1
	Next 40,000 MWh		4.25	Tier 2
	remaining MWh		3.28	Tier 3
	First 40,000 MWh	between 1 January 31 March 2016	6.51	Tier 1
	Next 40,000 MWh		3.83	Tier 2
	remaining MWh		2.95	Tier 3
	First 40,000 MWh	between 1 April 2016 and 30 June 2016	5.72	Tier 1
	Next 40,000 MWh		3.36	Tier 2
	remaining MWh		2.58	Tier 3
	First 40,000 MWh	between 1 July and 30 September 2016	4.86	Tier 1
	Next 40,000 MWh		2.85	Tier 2
	remaining MWh		2.20	Tier 3
	First 40,000 MWh	between 1 October and 31 December 2016	4.61	Tier 1
	Next 40,000 MWh		2.72	Tier 2
	remaining MWh		2.09	Tier 3
	First 40,000 MWh	between 1 January and 31 March 2017	4.16	Tier 1
	Next 40,000 MWh		2.45	Tier 2
	remaining MWh		1.88	Tier 3

	First 40,000 MWh	between 1 April and 31 June 2017	3.75	Tier 1
	Next 40,000 MWh		2.21	Tier 2
	remaining MWh		1.69	Tier 3
	First 40,000 MWh	between 1 July 2017 and 21 May 2018	3.37	Tier 1
	Next 40,000 MWh		1.99	Tier 2
	remaining MWh		1.52	Tier 3
	First 40,000 MWh	between 22 May and 31 December 2018	5.72	Tier 1
	Next 40,000 MWh		3.36	Tier 2
	remaining MWh		2.58	Tier 3
	First 40,000 MWh	on or after 1 January 2019	4.86	Tier 1
	Next 40,000 MWh		2.86	Tier 2
	remaining MWh		2.21	Tier 3
Small Biogas combustion	**Less than 200 KWth**	before 1 April 2016	8.44	N/A
		between 1 April and 30 June 2016	7.41	
		between 1 July and 30 September 2016	6.30	
		between 1 October and 31 December 2016	4.74	
		between 1 January and 31 March 2017	3.54	
		between 1 April and 30 June 2017	3.37	
		between 1 July 2017 and 21 May 2018	3.03	
		on or after 22 May 2018	4.74	
Medium biogas combustion	**200 kWth and above & less than 600 kWth**	before 1 April 2016	6.63	
		between 1 April and 30 June 2016	5.83	
		between 1 July and 30 September 2016	4.94	

		between 1 October and 31 December 2016	3.72	
		between 1 January and 31 March 2017	2.78	
		between 1 April and 30 June 2017	2.64	
		between 1 July 2017 and 21 May 2018	2.38	
		on or after 22 May 2018	3.72	
Large biogas combustion	**600 kWth and above**	before 1 April 2016	2.50	
		between 1 April and 30 June 2016	2.17	
		between 1 July and 30 September 2016	1.85	
		between 1 October and 31 December 2016	1.39	
		between 1 January and 31 March 2017	1.05	
		between 1 April and 30 June 2017	1.00	
		between 1 July 2017 and 21 May 2018	0.91	
		between 22 May and 31 December 2018	1.39	
		on or after 1 January 2019	1.18	

Note:

1. biomass, biomethane and ground/water source heat pump tier thresholds are detailed in sections 6.28 to 6.32 and 6.45 to 6.48 of Guidance Volume 2: Ongoing obligations and payments
2. Installations of the following eligible technologies must have been commissioned on or after 4 December 2013:
    - Solid biomass CHP
    - Air source heat pump
    - Deep geothermal
    - Medium biogas
    - Large biogas

A2: Coding scheme for product analysis

Based upon our literature review we developed an Excel spreadsheet for data collection. The following table gives an overview over the collected variables as well as definitions and coding rules:

Code name	Definition	Coding rule	Example
country	Country in which the tariff is sold	State the country: 1 - Germany 2 - Austria 3 - Switzerland 4 – United Kingdom	N/A
date_of_coding	Date of coding the tariff	Add the coding date in this format: DD/MM/YYYY	22/01/2019
name_provider	Name of the provider offering the tariff	Add the provider name	Good Energy Gas Limited
source_provider_name	Source provider is taken from	Indicate the source: **Germany:** 1 - Energie+Management 2 - Check 24 3 - Vervivox 4 - Energie+Management + Check 24 5 - Energie+Management + Verivox 6 - Energie+Management + Check 24 + Verivox sample **Austria:** 7 - E-Control 8 - Durchblicker.at 9 - E-Control and Durchblicker.at **Switzerland:** 10 - Verband der Schweizerischen Gasindustrie **United Kingdom:** 11 - OFGEM-List 12 - only in comparison portals 13 - OFGEM-List and comparison portals	N/A
biomethane_provider	Provider offers one or more biomethane tariff(s)	Indicate if the provider offers a biomethane tariff: 0 - No	N/A

		1 – Yes If not, coding is done for this provider.	
name_tariff	Name of the tariff	Add the tariff name	Life Energy
PLZ_tariff_found	Postal code the tariff has been coded for	Add the postal code used for coding values.	72622
biomethane_content	Share of biomethane of the tariff (%)	Indicate the share of biomethane of the tariff (1 - 100%).	10%
biomethane_feedstock	Feedstock/source material of the biomethane	Indicate the base material/feedstock of the biomethane in the tariff: 1 - Energy crops 2 - Waste 3 - Mix (energy crops and waste)	N/A
origin	Geographic origin/location of production sites	Where is the biomethane, the provider sells, produced? Please choose the according option: 1 - regional 2 - national 3 – international Regional is defined as "stated geographical proximity of generation and customers". National is defined as "within the national borders of the country the provider is located". International is defined as "beyond the national borders of the country the provider is located". Please choose the highest category regardless of production volumes: If 99% of the production are within the national borders and only 1% from another country this is still regarded as "international". Comments on this can be added in the next column	N/A
origin_comment	Geographic origin: Further information	If available add further information on the origin	"Our biogas comes from the SwissFarmerPower Inwil AG plant"

			"Biogas 100% from the canton of Fribourg" "from Vorarlberg for Vorarlberg" "Only produced in south Germany"
price	Yearly price of the tariff without any bonus payments for provider change or discounts	Indicate the total gross price of the tariff, without any bonus payments for provider change or discounts.	970.14 CHF
price_in_EUR	Yearly price of the tariff without any bonus payments for provider change or discounts in EUR	Indicate the total gross price of the tariff in EUR, without any bonus payments for provider change or discounts.	1356.22 €
provider_change_bonus	Amount of special payments for provider change in EUR	Indicate (if offered) the total amount of payments for changing the provider.	100 €
tariff_conditions	Description of tariff details (contract term, duration of price guarantee, period of notice)	Give a short description of the contract details (i.e. contract term, duration of price guarantee, period of notice)	"12 months first contract term, price guarantee until 31.12.2018, 1 month period of notice"
number_labels	Number of labels associated to the tariff	How many labels are listed for this tariff (e.g. customer labels, price labels, satisfaction labels…)? Please add the according information for each label in the next columns. Only count and add further information for labels that are clearly associated to the tariff, not the provider -i.e. those on the tariff homepage, not those on the general provider homepage	3
name_label_1	Name of the first label ascribed to the tarif	Add label name	"naturemade star" "Top local supplier 2017"
info_label_1	Further information/short description of label 1	Please add a short description of the available information (i.e. year of label, awarding institution…)	"Approved biogas product" "Awarded by the Energy Consumer Portal"
The described procedure for the first label was repeated for all further labels.			
comparable_gas_tariff	Availability of a comparable regular	Does the provider offer a comparable gas tariff	N/A

	(non-biomethane) gas tariff:	which does not contain biomethane (=regular gas tariff) with comparable tariff conditions (contract term, duration of price guarantee, period of notice)? 0 - No 1 – Yes	
name_comparable_gas_tariff	Name of the comparable gas tariff	Indicate the name of the comparable regular gas tariff from this provider.	“TIGAS Best Comfort”
price_comparable_tariff	Yearly price of the comparable tariff without any bonus payments for provider change or discounts	Indicate the total gross price of the comparable regular gas tariff of this provider, without any bonus payments for provider change or discounts.	715.77 GBP
price_comparable_tariff_EUR	Yearly price of the comparable tariff without any bonus payments for provider change or discounts in EUR	Indicate the total gross price of the comparable regular gas tariff of this provider, without any bonus payments for provider change or discounts in EUR.	1,226.20 €
conditions_comparable_tariff	Divergent tariff conditions of the comparable tariff compared to the biomethane tariff	Indicate the deviating conditions of the regular gas tariff compared to the biomethane tariff of this provider (e.g. other contract terms, durations of price guarantees or period of notice)	“period of notice: 10 working days”
provider_type	Provider type/geographic location of operation	In which area does the provider operate in general/with other products (e.g. non-RE-energy, gas, mobility)? 1 - regional 2 - national 3 - international Regional is defined as "stated geographical proximity of provider and customers“. National is defined as "within the national borders of the country the provider is located" International is defined as "beyond the national	N/A

		borders of the country the provider is located"	
purely_green_supplier	Supplier offers only green/renewable-based products	Is the provider offering the tariff a "green-only"-provider? Does he offer exclusively green tariffs, products and services? 0 - No 1 - Yes	N/A
commercial_orientation	Commercial orientation of the supplier	Indicate the commercial orientation of the supplier, based on the legal form and structure of shareholders: 1 - Purely commercial 2 - Municipal utility 3 - Cooperative	N/A
add_contribution	Additional contributions of the supplier	Indicate if the supplier mentions any further/additional contributions (e.g. donation to an environmental organization/project like WWF) 0 - No 1 - Yes	N/A
comment	Comments and remarks on this tariff	Add comments, anomalies, distinctive features of the tariff here for discussion	"Individual biogas share on request"
For all variables/codes we added the following alternatives: **-88 - information not on homepage and not upon request** **-99 - Missing Value**			

Appendix B to Invisible, intangible, irrelevant, yet inevitable? Qualitative insights into consumer perceptions of heating tariffs and drop-in renewable gases in the German domestic heating market

B1: Socio demographic information as well as residential and heating situation of IPs

IP	Age	Sex	Household size	Financial situation[6]	East / West Germany	Occupation	Educational level	Housing situation	Heating type/ energy source	Residential area
IP01	40	male	4 (incl. 2 kids)	"All right"	West	Teacher	University diploma	Single-family house, own property	Oil heating Tiled stove Hot water heating in summer with heat pump	rural
IP02	47	male	*N/A*	"Very convenient"	West	Managing partner in an IT firm	PhD	Single-family house, own property	Oil heating	rural
IP03	71	male	5 (incl. daughter and grandchildren)	"Solid"	West	Retired, previously: special education teacher	University diploma	Single-family house, own property	Pellet heating with solar thermal support	rural
IP04	37	female	3 (incl. 1 kid)	"Good"	West	Teacher	University diploma and master	Single-family house, own property	Gas-solar thermal combination	rural
IP05	47	female	4 (incl. 2 kids)	"Good"	West	Architect	University diploma	Single-family house, rent	Gas heating Tiled stove	urban
IP06	78	female	*N/A*	"Not bad"	West	Retired, previously: teacher	University state exam	Single-family house, own property (Landlord in another building)	Oil heating (Gas heating in rented out building)	rural
IP07	38	male	4 (incl. 2 kids)	"Solid"	West	Teacher	University diploma	Single-family house, own property	Heat pump (with electricity from own PV system)	rural
IP08	45	male	4 (incl. 2 kids)	"Very convenient"	West	Technician	Master carpenter	Semi-detached house, own property (Professionally manages energy supply of a municipal housing association)	Wood stove Gas heating	urban
IP09	64	male	2	"Good"	West	Electrician	Vocational baccalaureate, vocational training	Single-family house, own property	Gas heating	rural

[6] Direct quotes as indicated by the interviewees

IP10	65	male	2	“Good”	West	Property manager	Secondary school	Two-family house, own property (Professionally manages several properties including energy supplies)	Oil heating	rural
IP11	72	male	2	“Good”	West	Retired, previously: Electronics developer	Electrical engineering studies	Single-family house, own property	Gas heating	rural
IP12	53	female	2	“All right”	West	Preschool teacher	Vocational baccalaureate, vocational training	Single-family house, own property (Landlord in another building)	Oil heating (Gas heating in rented out building)	rural
IP13	40	male	1	“All right”	West	Wholesale and foreign trade clerk	Secondary school, vocational training	Condominium in an apartment building	Oil heating Electric underfloor heating	urban
IP14	51	male	2	“Good”	West	Man of independent means, former owner of four companies	Secondary school, master roofer	Semi-detached house, own property (Owner of several real estate and properties)	Gas heating (Oil and gas heating in rented out buildings)	urban
IP15	32	female	4 (incl. 2 kids)	“Very good”	West	Student	University Bachelor	Single-family house, own property	Gas heating	rural
IP16	63	male	*N/A*	“Good”	West	Business economist, administration	Advanced technical college entrance qualification, trained business economist	Terraced house, own property	Gas heating	urban
IP17	41	female	2	“Below the average”	East	Social worker	University Magister Artium	Flat in apartment building, rent	Gas heating Tiled stoves	rural
IP18	44	female	4 (incl. 2 kids)	“All right”	West	Medical assistant	Secondary school, vocational training	Terraced house, own property	District heating	rural
IP19	66/63	female/ male	2	“Normal”	West	Housewife Garden designer	Secondary school (both)	Single-family house, own property	District heating	rural
IP20	68	male	*N/A*	“Good”	East	Retired, previously: information technician	University diploma	Semi-detached house, own property	Gas heating	rural
IP21	42	male	2	“Good”	East	Process Manager	University diploma	Single-family house, own property	Gas heating PV support for hot water production	urban
IP22	42	female	2	“Good”	East	Research associate and working group leader	University diploma	Semi-detached house, rent	Gas heating	urban

B2: Interview guideline

Project introduction	In our project (BGA-PtG)² -please don't let the title confuse you- we deal with how the technology 'Power-to-Gas' can be integrated into the operation of biogas and biomethane plants. Our project partners focus on the technical aspects and possibilities. We, on the other hand, are interested in how potential customers see the regenerative gases stemming from this combination. To this end, I will ask you a few open questions in a moment. The important thing is: there are no right or wrong answers. You simply tell us what you think. You also don't need any prior technical knowledge. Of course you can ask questions at any time! The whole thing should take about 40 minutes. We will conduct a total of about 20 interviews throughout Germany. Your data will of course be treated confidentially and processed anonymously. We will be happy to give you access to our results! I would like to read you our data protection regulations and record this already, if you agree.
Interest in own energy supply and prior knowledge of biogas and PtG-technologies	1. *[Initial thoughts]* Tell me, what do you think about when you think about your energy supply? 1.1. *[Intensity]* Do you often think about your energy supply, does it play a big or a rather small role? 1.2. *[Occasion]* Are there special occasions when you think about your energy supply? 2. *[Manufacturing process]* To what extent are you interested in the manufacturing process for energy supply? Why (not)? 2.1. *[Technology understanding]* To what extent do you want to understand, for example, how a particular technology works? 2.2. *[Other products]* Is this different for other products and services? If yes, for which? 3. *[Prior knowledge of Biogas/PtG]* Our project is about biogas plants and power-to-gas plants: To what extent have you already dealt with these plants? 3.1. *[Prior knowledge of feedstock]* To what extent do you know which feedstock is used in biogas or PtG plants? 3.2. *[Problem awareness]* Do you have a critical attitude? Do you associate any of these technologies with problems or challenges? 4. *[Mass balance]* Have you ever heard of the so-called mass balance?
Decision process for a heating system and heating tariff	1. *[Influence]* Do you have any influence on the choice for your heating system or the choice for a specific supplier? 1.1. *[Heating system type]* What type of heating system do you use? 1.2. *[Supplier]* Where do you get your fuel from? 2. *[Calculus]* Why did you choose this particular heating system or energy carrier? 2.1. *[Price)* 2.2. *[Space]* 2.3. *[Efficiency]* 2.4. *[Climate change]* 2.5. *[Brand]* 2.6. *[Trust in manufacturer]* 2.7. *[Technology/energy carrier lock-in]* 3. *[Alternatives]* To what extent did you consider other heating systems or energy carriers? Which systems did you consider? 4. *[Alternative biomethane]* Have you ever thought about a biomethane tariff? Why (not)? 5. *[Replacing heating systems]* Are you thinking about replacing your heating system? Which systems do you consider?

Evaluation of biomethane and SNG

1. *[Prior knowledge]* To what extent have you heard of biomethane?

[Info segment biomethane] Biomethane is an energy carrier that can be used like natural gas. Because it is produced from biogas, biomethane is largely CO_2-neutral. Compared to natural gas, biomethane saves about 30% of CO_2 and compared to heating oil it saves almost 50% CO_2. Biogas can be obtained from organic waste or energy crops and upgraded to biomethane. Another option is to convert CO_2 produced in biogas upgrading plants into biomethane together with hydrogen produced using the power-to-gas technology. Biomethane can be obtained from the natural gas grid.

2. *[General interest biomethane]* After this information, would biomethane be interesting for you? Why (not)?
   - 2.1. *[Price]*
   - 2.2. *[Subsidies by the state]*
   - 2.3. *[Talking to others]* If you were sourcing biomethane, would you tell others about it?
   - 2.4. *[Own identity]* And, thinking about yourself, how does biomethane fit with your own beliefs?
   - 2.5. *[Information sources]* How would you find out about biomethane?
     - *2.5.1. [Friends and acquaintances]*
     - *2.5.2. [Social networks]*
     - *2.5.3. [Dealers]*
     - *2.5.4. [Press]*
     - *2.5.5. [Internet]*
     - *2.5.6. [Labels and certificates]*
   - 2.6. *[Trust]* What about trust in the supplier, is that relevant?
   - 2.7. *[Nature]* In what way do you associate biomethane with nature?
   - 2.8. *[Regionality]* And what role does it play where the supplier is located from whom you obtain the biomethane (e.g., nearby or in another state)?
   - 2.9. *[Provider type]* And how is the type of provider relevant for you? So whether it is, for example, a municipal utility or some other type of company.
   - 2.10. *[Importance switching]* How important is it to you that you can switch between biomethane and natural gas?
   - 2.11. *[Religion]* What role do your religious beliefs play in considering whether biomethane is of interest to you?
   - 2.12. *[Politics]* What role do your political beliefs play in considering whether biomethane is of interest to you?

[Info segment fuel vs. food] As mentioned above, biomethane can be produced from various materials: For example, energy crops (such as maize) or from waste. One problem that some people see in energy crops is the so-called "food vs. fuel problem" – on agricultural land where energy crops are grown, food could also be grown.

3. *[Feedstock]* What role does the feedstock from which biomethane is produced play for you?
4. *[Food vs. fuel] T*o what extent does the so-called food vs. fuel problem play a role here?

[Info segment landscape changes] The additional cultivation of energy crops can also change the landscape. Critics speak of the so-called "maizification of the landscape".

5. *[Landscape]* What role does landscape play in your evaluation of biomethane?

[Info segment additional traffic] Furthermore, the cultivation of energy crops can also increase agricultural traffic – e.g. crops have to be harvested and transported away.

6. *[Agricultural traffic]* To what extent does the idea of additional agricultural traffic influence your assessment?

7. *[Evaluation SNG]* How does your assessment change if I tell you that methane can also be produced from surplus electricity from renewable energy plants via a few detours?

	[Info segment mass balance] If you decide to choose a gas product that contains biomethane or gas from PtG plants, the chemical composition of the gas you buy remains the same - you don't get "green molecules", but the same gas as everyone else. What changes, however, is the composition of the total gas in the gas grid: for the amount of biomethane you pay your supplier for, he guarantees that the same amount will be fed into the gas grid. This makes the "total gas" a little greener for everyone, but everyone still gets the same gas. *8. [Evaluation mass balance]* What role does the fact play, that you are still using the same product despite having purchased biomethane?
Demographics	*[Introduction demographics]* The following more personal questions are important for us to be able to evaluate or classify your previous answers. If you feel uncomfortable answering individual questions, you can also omit them. 1. *[Sex)* 2. *[Age]* 3. *[Occupation]* 4. *[Highest level of education]* 5. *[Residential situation]* How do you currently live? 6. *[Environmental awareness]* How would you describe your environmental awareness? 7. *[Cultural activities]* What role do cultural activities play in your everyday life? For example, do you like reading or going to museums? 8. *[Financial situation]* How would you describe your financial situation? 9. *[Social network]* How much social contact do you have and what do you do with them? 10. *[Values and norms]* What do you think about values and norms? How important are these to you?

B3: Coding scheme consumer interviews

Topic	*Sub-topic level 1*	*Sub-topic level 2*	*Example*	*Assigned IPs*
Selection criteria for current tariff	Provider-related	Offering of renewable energies	"Because they generate their electricity with hydropower and wind energy and so on, and its electricity mix contains significantly less coal-fired electricity than the German electricity mix as a whole". (IP07)	IP07, IP09, IP12
		Regionality	“So regionality is not entirely unimportant to me, that's why we get our supply from the regional supplier.” (IP04)	IP04, IP05, IP07, IP09, IP11, IP16
		Service quality	"Because I think the provider can only do it through service in the end." (IP21)	IP21
		Security of supply, reliability and trust	“And with these other offers and so on, I've heard so many bad things about them, that you sign contracts and they can't deliver afterwards, and stories like that.” (IP09)	IP06, IP09, IP14, IP20
		Preferences for specific legal forms/ provider types	“Then it's important to me what the ownership structure is behind it. Is it a large corporation or rather a smaller association, a cooperative or whatever?"	IP04
		Provider loyalty	"Well, exactly, so I'll just say that I've had my gas provider since I was a student [...]" (IP22).	IP09, IP11, IP12, IP14, IP20, IP22
		Regular change of provider	“For example, I changed my gas supplier because the basic fee was too high for me. So I changed to another one.” (IP06)	IP04, IP05, IP06, IP10, IP12
	Tariff-related	Costs	"And at the same time, I also pay attention to the price […]” (IP04)	IP01, IP04, IP06, IP09, IP10, IP12, IP14
		Environmental and climate concerns	"Concerning the heating oil I buy, I pay attention to that/ I choose ecological sound products [...]". (IP01)	IP01, IP04, IP14
		Unawareness and insecurity about own eco-gas or biomethane tariff	“The tariff, good question. I think it's the complete eco tariff. I don't even know if there are different gradations, but we get completely, one hundred percent, I mean, that's this one hundred percent eco gas tariff.” (IP22)	IP04, IP05, IP09, IP22
		Unawareness (other energy carriers)	“With gas, I don't really know where it comes from. (...) Yes, I can't elaborate on that either, because I can't say anything about it now.” (IP06)	IP06, IP15
		Indifference	"I pay the bill, I don't care where it comes from." (IP18)	IP14, IP18

Evaluation of renewable gases	Prior knowledge of biogas technology	Technology is known	"I am aware of the basic production method, I know how it works." (IP07)	IP03, IP06, IP07, IP09, IP12, IP16, IP17, IP20, IP21, IP22
		Technology is known little	"Through the IHK I know a bit about biogas plants, but I think I have a very diffuse half-knowledge." (IP05)	IP04, IP05, IP10, IP19
		Personal involvement	"Biogas plants are more common, because you can see them just here -we live, let's say, relatively rural and there you can see from time to time at some farms the large containers, where biogas is produced […]." (IP09)	IP03, IP06, IP07, IP09, IP12, IP16, IP19, IP20, IP21, IP22
		No prior knowledge	"I haven't heard about it before." (IP15)	IP01, IP11, IP13, IP14, IP15, IP18
		Interview as trigger	"I mean, you've given me the idea that I've already thought about it a little bit, but that's all, right? (IP11)	IP10, IP11
	Prior knowledge of PtG technology	Technology is known	"So power-to-gas: Do I understand it correctly, that it's about, for example, a wind power plant that produces too much at the moment that it can't be fed into the grid, that they just do something else useful with it, for example." (IP02)	IP02, IP03, IP07
		Technology is known little	"[…] With power to gas, from my point of view there are only a few demonstration plants. Exactly. But I'm not that far into it now [...]" (IP22).	IP04, IP09, IP10, IP22
		No prior knowledge	"Never heard of it before today." (IP17)	IP01, IP05, IP08, IP11, IP12, IP13, IP14, IP15, IP16, IP17, IP18, IP20
		Interview as trigger	"So in preparation for the interview, I took a quick look at some sources and otherwise looked on the internet, of course, no question about it." (IP10)	IP10, IP11, IP17
	Valuing statements on PtG technology	Neutral and uncritical	"So basically I'm open about all that kind of stuff." (IP01)	IP01, IP04, IP07, IP09, IP14, IP15, IP22
		Positive	"I find that totally exciting." (IP21)	IP21
		Negative: Low efficiency	"Yes, the efficiency is probably still rather modest at the moment". (IP02)	IP02
		Negative: Costs	"With power to gas, yes, I still think it's quite expensive at the moment." (IP22)	IP22

		Negative: unclear availability of surplus electricity from renewable sources	"Well, with power to gas, if I remember, the question is also where does the surplus electricity come from." (IP22)	IP22
	Valuing statements on biogas technology	Neutral and uncritical	"I don't think you can be critical of something if you don't know how it works at first." (IP13)	IP01, IP02, IP04, IP06, IP07, IP09, IP13, IP14, IP15, IP21, IP21, IP22
		Positive: Energetic use of waste	"I have always thought that it is a good thing to produce biogas from waste, from manure, and then use it to generate energy." (IP03)	IP03, IP14, IP22
		Positive: Use of renewable energy	"Yes, today I heat my house with gas, natural gas, and my vehicle is powered by fuel, fossil fuel if you like. And they are even thinking about doing it with gas, with biogas. (IP11)	IP11
		Negative: Maize monocultures	"It bothers me when maize is permanently cultivated here for biogas plants. I would like it to be a bit different [...]" (IP10).	IP03, IP08, IP10, IP20, IP21
		Negative: "Misuse" of crops	"In a certain way, against the background of not using useful plants in the original sense, that is a bit strange at first [...]" (IP17)	IP17
		Negative: Lack of arable land	"Yes, I could imagine that at some point there might be a critical mass where people say that if you produce so much biogas, you need so much land". (IP21)	IP21
		Negative: Usage of large machineries	"[...] but it's purely designed for that with the huge machines and the monocultures." (IP08)	IP08
		Negative: Dependency on federal subsidies	"So it just has to work when you say that you've earned money for so many years now and maybe also initiated the whole thing through subsidies and got it going, that's all well and good, but then it has to run itself, or you just have to be satisfied with the little that you get". (IP08)	IP08
		Negative: Long arrival routes	"[...] I even know someone who drives 50 kilometers with trucks to drive the maize back and forth to throw it into the biogas plant. That bothers me a bit too." (IP08)	IP08
		Negative: Loss of biodiversity	"That meadows are harvested before flowering and processed into biogas. Of course, that does our insects the least good." (IP03)	IP03
	Interest in biomethane	Principal interest signaled	"I'll say yes. It could be interesting." (IP11)	IP01, IP02, IP04, IP05, IP06, IP07, IP08, IP09, IP11,

				IP12, IP13, IP14, IP15, IP16, IP17, IP18, IP20, IP21, IP22
		Positive: Environmental and climate impacts	"Because, as I said, I'm an environmentally minded person and I don't think it's bad to switch to something like that if it's not a problem and doesn't have any disadvantages." (IP15)	IP04, IP09, IP12, IP15
		Positive: CO_2 neutrality/savings	"Well, if less CO_2 is produced, I think it's interesting." (IP05)	IP04, IP05, IP18, IP21
		Positive: Use of waste products	"[...] so if it is made from waste, it is also interesting." (IP05)	IP05, IP14
		Positive, but perceived restrictions: Uncertainties about supply options	"But I don't know if there is a possibility to have the biomethane delivered to our house." (IP06)	IP06, IP16
		Positive, but perceived restrictions: Uncertainties about system compatibility	"If the gas network allows it, and it can also be used in a conventional burner, this could be interesting." (IP17)	IP17
		Positive, but perceived restrictions: Uncertainties about security of supply	"[...] if it is guaranteed that it can be produced again and again [...]". (IP18)	IP18
		No principal interest signaled	"Because I stick with my oil." (IP10	IP01, IP02, IP09, IP10, IP11
		Negative: Unavailability of gas in the building	"[...] so I don't have a gas grid connection here [...]"	IP01, IP10
		Negative: Preferences for the	"But not yet more interesting than the heating system that is actually being considered now." (IP02)	IP02, IP10

		own/another energy carrier		
		Negative: High age	"Yes, I could say now, due to my age probably, I will no longer come to the idea to switch." (IP11)	IP11
	Role of price in the evaluation of biomethane	Important	"Yes, price is unfortunately always an issue at the moment, even when it comes to heat and hot water." (IP17)	IP01, IP02, IP04, IP05, IP06, IP08, IP09, IP10, IP11, IP14, IP15, IP16, IP17, IP18, IP19, IP20, IP21
		Not important	"So for me, now with natural gas, the price didn't play a role, but we have already, yes, we have always opted for renewables, and for me the price would not have been a deciding factor." (IP22)	IP22
		Acceptance of price surpluses	"I would be willing to pay a little more." (IP05)	IP01, IP04, IP05, IP07, IP09, IP14, IP15, IP20, IP21, IP22
	Role of environmental and climate protection in the evaluation of biomethane	Considered as important	"So, if a solution is economically attractive and climate-friendly at the same time, then of course it makes it very attractive." (IP02)	IP01, IP02, IP03, IP04, IP06, IP08, IP09, IP12, IP14, IP15, IP16, IP17, IP18, IP19, IP20
		Considered as not important	"Not at all important. So as long as we talk about climate change in Germany, but still don't clean up the tree damage from Kyrill in 2007, I'm not talking about climate change." (IP10)	IP10
	Role of "food vs. fuel" in the evaluation of biomethane	Considered as problematic	"Yes, I find it difficult when you use food, so to speak, a product that would also be food, when you use it for energy supply, I consider this problematic."	IP05, IP07, IP08, IP14, IP14, IP15, IP21
		Considered as problematic, however relativized	"But I haven't weighed up how sustainable or useful it is to burn plants there rather than bringing them to the food market." (IP17)	IP01, IP04, IP09, IP11, IP12, IP13, IP14, IP15, IP16, IP17, IP18, IP21
		Not considered as problematic	"So I mean the way it's going now I don't find it a problem, no." (IP06)	IP06, IP10

		Problem is unknown	"Aha, the term is new to me. You mean that food is converted into electricity or gasified?" (IP06)	IP06
		Diffuse problem perception	"If it's the maize that I could eat, so to speak, I would be interested, yes. It just makes more sense to me to use the waste, so to speak. But the other may also work quite well." (IP01)	IP01, IP04, IP09, IP11, IP12, IP13, IP14, IP15, IP16, IP17, IP18, IP21
		Attributed to foreign countries	"I don't think that we have any problems in Germany because of food cultivation and so on. In Germany, we're actually doing pretty well here. In other countries, it looks different again." (IP13)	IP04, IP13, IP16
	Role of regionality in the evaluation of biomethane	Considered as important	"So regionality is not entirely unimportant to me, that's why we're sourcing from the regional provider." (IP04)	IP01, IP04, IP06, IP07, IP08, IP09, IP11, IP15, IP16, IP18, IP19, IP21, IP22
		Considered as not important	"As long as the provider can deliver, I don't really care." (IP13)	IP02, IP05, IP06, IP10, IP13, IP14, IP20, IP21
		Preference for regional provider	"As I said, preference would now be our local provider." (IP09)	IP01, IP04, IP06, IP07, IP08, IP09, IP11, IP16, IP18, IP19
		Preference for regional production	"[…] if I'm already thinking about sourcing biomethane, I'd think it would be cool if it was from here in the region." (IP15)	IP12, IP15, IP21, IP22
	Role of provider type in the evaluation of biomethane	Considered as important	"If I could choose, yes. Then I would not opt for big energy suppliers but rather for a smaller one probably." (IP22)	IP04, IP08, IP09, IP10, IP14, IP16, IP18, IP19, IP20, IP22
		Considered as not important	"Whether it's a private company or not, or whether it's from the state, the city or whatever, I don't really care." (IP13)	IP02, IP06, IP11, IP12, IP13, IP14, IP15, IP17, IP21
		Preferred provider: Municipal utility	"I would prefer a municipal utility. With private providers, yes, a private provider always has the background, they have to make money with it." (IP20)	IP04, IP09, IP10, IP18, IP20

		Preferred provider: Energy cooperative	"Then it is important to me which ownership structure is behind it. Is it a large corporation or rather a smaller association, a cooperative or whatever?" (IP04)	IP04, IP16, IP22
		Preferred provider: Established and reliable	"I'm a bit old-fashioned, in this regard: […] I'd rather take someone who's been doing this for ten years somehow." (IP08)	IP08, IP18, IP19
	Evaluation SNG	Positive	"That would be the optimal thing, of course, that's already clear, if that's possible." (IP19)	IP01, IP02, IP04, IP05, IP06, IP08, IP11, IP12, IP13, IP14, IP15, IP16, IP17, IP19, IP20, IP21, IP22
		SNG as improvement over biomethane	"It's even more positive than biomethane, so to speak." (IP15)	IP15
		Importance of using surplus electricity stressed	"So as I said, I'm immediately more interested in it when I say, okay, there's too much electricity, you can use it for something like that, and so it's easier to produce heating energy. I think that's good." (IP08)	IP01, IP02, IP05, IP08, IP13, IP17, IP22
		Negative: Direct storage of electrical energy preferred	"For the surplus electricity, please find a reasonable storage place so that I have electricity at night […] The electrical energy must be stored." (IP10)	IP10
		Negative: Efficiency losses	"That is another step. I have to do the storage after the first step, not after the second." (IP10)	IP10
		Negative: Costs	"I mean, I'm taking another step that's costing me money." (IP10)	IP10

B4: Information on interviewed experts and participants in the focus groups

FG/EX	Sector	Function
EX1	Energy Provider	Strategy and Digitalization
EX2	Energy Trading, Consulting, Plant Operation	Managing Director
EX3	Plant Operation	CEO
EX3	Plant Operation	Sales
FG1	Research and Development	Coordination of projects related to Bioenergy
FG1	Consulting	Head of Innovation Network related to Power-to-X
FG1	Energy Sector Association	Team Leader Renewable Gases
FG1	Plant Construction	Product Development Manager PtG
FG1	Industry Association	Unit Head
FG1	Energy Provider	Business Development Biomethane Trading
FG1	Energy Sector Association	Team Leader hydrogen
FG1	Automotive	Business Development PtG
FG1	Plant Construction	Product Development Manager PtG
FG2	Energy Provider	Head of Sales Gas Trading
FG2	Energy Provider	Head of Capacity and Asset Management
FG2	Plant Construction	Technical Sales Methanation
FG2	Energy Provider	Energy Policy Specialist
FG2	Research and Development	Team Leader Process Monitoring Biological Methanation
FG2	Project Development	Project Manager Future Energies
FG2	Energy Provider	Head of Energy Dispatching
FG3	Financial Sector	Senior Energy Advisor
FG3	Consulting	Trade Advisor Renewable Gases
FG3	Energy Trading, Consulting, Plant Operation	Managing Partner
FG3	Certification	Head of Green Gas Certification
FG3	Chemical Industry	Circular Economy Expert
FG3	Plant Construction	Chief Technical Officer
FG3	Energy Provider	Managing Director

B5: Coding scheme expert interviews and focus groups

Topic	*Sub-topic level 1*	*Sub-topic level 2*	*Example*	*Assigned EXs/FGs*
Evaluation of biomethane market	Only few "persuaders"/small market	-	"[…] this private customer market is relatively small." (EX2).	EX1, EX2, EX3, FG1, FG2, FG3
	Price and costs	Price-driven market	"But ultimately, it all comes down to price." (EX1)	EX1, EX2, EX3, FG1, FG2, FG3
		Price difference compared to fossil products	"Well, I have another aspect that is also an obstacle for private customers, and that is of course the price difference to fossil fuels (or nuclear energy products in the electricity sector)". (FG3)	EX1, FG3
		Customers getting used to lower prices from the renewable electricity market	"I can't explain it myself, but how did it work with electricity? How do you get customers today to buy one hundred percent renewable energy in electricity, but with gas there is no market for it at all? The price difference is much lower. It's much, much lower, for example, with green electricity certificates." (FG1)	FG1
	Lack of consumer knowledge and confusion	-	"That is also a second issue, precisely this topic of compensation, greenwashing: The customers are not aware of that either, because in the end they lump eco-, bio-, climate gas, everything together." (FG3)	EX1, FG1, FG2, FG3
	Competition from "eco-gas" (compensated gas products)	-	They simply talk about biomethane. But it's so opaque right now, this eco-gas market, these eco-gas products. Because some [providers] plant trees somewhere and so on. And that's difficult for the end customer to understand what he's actually getting there." (FG2)	EX1, FG1, FG2, FG3
	Importance of trust building through labeling and certification	-	""The background is simply, that we can tell our customers a lot: "Yes, it's green, yes, renewable electricity is used". That's why a certificate like this is relatively important for the whole topic, so that a third independent party confirms it. (FG2)	FG2, FG3
	Importance of trust building through complete proof of origin	-	"[…] so if you then manage to perhaps also establish this plant reference, that you say, okay, this [gas] now comes from this or that plant […]" (EX2)	EX2, FG1, FG3
	Raw material related	Consumers prefer biomethane stemming from	"[…] that a customer feels more comfortable using biomethane from waste than from maize, i.e. from renewable resources". (EX2)	EX1, EX2, FG1

		waste over energy crops		
		Consumers consider the “food vs. fuel” discussion critically	"[…] because the product is not attractive enough, because of this whole “food vs. fuel” discussion." (EX2)	EX2, FG1, FG3
	Low-involvement of consumers/no conspicuous consumption possible	-	“[…] I think the group of people of conviction is small, because heating is just something totally un-erotic. So you drive your electric car and show it off. But you can't show biomethane in the heating system.” (EX03)	EX3
Evaluation of SNG market	Only few "persuaders"/small market	-	“[…] because we have simply found that the customer is not willing to pay the extra price or that there are only very, very few customers." (FG1)	EX2, FG1
	Price and costs	Price-driven market	“But essentially the price, that is certainly decisive." (EX2)	EX2, FG1
		Customers getting used to lower prices from the renewable electricity market	“And because switching from normal electricity to green electricity was also totally cheap for the customer, because in both cases he has to pay the EEG surcharge. Yes? And then the additional costs were very manageable. And that's the kind of world we have to get into with gas supply." (FG1)	FG1
	Competition from “eco-gas” (compensated gas products)	-	“So I personally see the problem that green power or green gas is just such a huge bubble. Just like in electricity. Now I can practically buy my green electricity from Norway via RECS certificates and with 0.1 cents my electricity is already green. The situation is similar in the gas industry. Somehow it's called natural gas, green gas, [...]" (EX1).	EX1
	Importance of trust building through complete proof of origin	-	"We also see supply chain transparency through digitalization as a great opportunity. We still see block chain as being a long way away from realization.” (FG3)	EX2, FG3
	Higher acceptance of SNG compared to biomethane	-	"But, I'll say, from the consumer acceptance, I think you can market green hydrogen or power-to-gas better, it has a higher acceptance." (EX2)	EX2, EX3, FG1
	No “food vs. fuel” discussion with SNG	-	“So I guess the acceptance of this SNG would be high, because even with the worst thinking there is no food vs. fuel et cetera.” (EX3)	EX3

Appendix C to Renewable gases in the heating market: Identifying consumer preferences through a Discrete Choice Experiment

C1: 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%*

C2: Labels used in this study (third label is the fake label)

C3: Used price levels 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%*

C4: Residential and heating situation of the whole sample

Variables	***Values***	***Sample***
Type of building (n = 512)	*Single-family house*	*36.9%*
	Terraced house	*17.0%*
	Apartment building (3-12 flats)	*38.5%*
	Large apartment building (more than 12 flats)	*7.6%*
Construction year of building (n = 512)	*Before 1969*	*24.4%*
	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%*
	Partial refurbishment	*43.1%*
	Conventional refurbishment	*21.4%*
	Future-oriented refurbishment	*8.7%*
Living space (sqm, n = 512)	*Median*	*90-99*
Ownership status (n = 512)	*Tenant*	*54.5%*
	Owner	*45.3%*
	Unknown	*0.2%*
Calculated yearly costs for heating and hot water (€, n = 522)	*Mean*	*845.91*
	SD	*489.89*
	Min	*99.90*
	Max	*2904.10*
Current gas supplier (n = 512)	*Local basic supplier (i.e. municipal utility)*	*58.4%*
	Other local supplier	*14.6%*
	National supplier	*23.2%*
	Unknown	*3.7%*
Knowledge about biomethane as natural gas substitute (n = 512)	*Unknown*	*56.4%*
	Known	*43.6%*
Purchase of biomethane (n = 223, only those knowing about biomethane)	*Yes*	*20.6%*
	No, but considered	*60.5%*
	No, not considered	*14.3%*
	Do not know	*4.5%*

C5: Socio-demographic and residential information of different consumer groups

		Knowledge biomethane		***Renewable electricity at home***	
		Unknown	***Known***	***No purchase***	***Purchase***
	n:	*289*	*223*	*295*	*217*
Sex	*Female*	*38,4%*	*41,3%*	*43,1%*	*35,0%*
	Male	*61,2%*	*58,7%*	*56,6%*	*65,0%*
	Diverse	*0%*	*0%*	*0,3%*	*0%*
Age	*Mean*	*46,14*	*36,91*	*41,95*	*42,50*
Household income (net)	*Less than 1000€*	*7,6%*	*4,9%*	*7,5%*	*5,1%*
	1000-1999€	*18,7%*	*13,0%*	*18,0%*	*13,8%*
	2000-2999€	*28,7%*	*22,9%*	*25,8%*	*26,7%*
	3000-3999€	*19,0%*	*24,2%*	*19,0%*	*24,4%*
	4000-4999	*12,1%*	*17,5%*	*14,2%*	*14,7%*
	5000€ and more	*9,3%*	*11,2%*	*9,2%*	*11,5%*
	No answer	*4,5%*	*6,3%*	*6,4%*	*3,7%*
Highest educational achievement	*No formal education*	*3,1%*	*3,1%*	*5,1%*	*0,5%*
	Still attending	*7,3%*	*9,0%*	*10,8%*	*4,2%*
	Finished vocational training	*51,0%*	*30,0%*	*42,4%*	*41,2%*
	Master craftsman training	*13,2%*	*14,3%*	*15,3%*	*11,6%*
	Bachelor degree	*6,3%*	*14,3%*	*7,8%*	*12,5%*
	Diploma, Master or PhD degree	*19,1%*	*29,1%*	*18,6%*	*30,1%*
Type of building	*Single-family house*	*35,3%*	*39,0%*	*32,9%*	*42,4%*
	Terraced house	*16,6%*	*17,5%*	*14,6%*	*20,3%*
	Apartment building	*40,8%*	*35,4%*	*43,4%*	*31,8%*
	Large apartment building	*7,3%*	*8,1%*	*9,2%*	*5,5%*
Calculated yearly costs for heating and hot water (€)	*Mean*	*857,57*	*825,15*	*852,99*	*830,48*
	SD	*493,31*	*487,24*	*497,95*	*480,93*
Current gas supplier	*Local basic supplier*	*54,3%*	*63,7%*	*61,7%*	*53,9%*
	Other local supplier	*11,1%*	*19,3%*	*13,2%*	*16,6%*
	National supplier	*30,4%*	*13,9%*	*19,7%*	*28,1%*
	Unknown	*4,2%*	*3,1%*	*5,4%*	*1,4%*
Purchase of renewable electricity at home	*Yes*	*34,9%*	*52,0%*		
	No	*48,1%*	*36,8%*	*N/A*	*N/A*
	Unknown	*17,0%*	*11,2%*		