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Assessment of Stakeholder Perception of Implementing Power-to-Gas in the Biogas Sector: Implications for Risk Governance

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In memory of my mother, Santa Tanilada Sierra Guerrero (05/07/1961 – 08/10/2006)
and my father, Felipe Pérez Méndez (09/22/1950 – 08/11/2012)

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Abstract

The connection of power-to-gas (PtG) with biogas facilities to convert excess renewable electricity into biomethane represents an innovation in the biogas industry. This concept could play a role in stabilizing the German renewable energy system and make the biogas value chain and derived products more competitive and environmentally friendly. With increasing interest in this technology, potential risks, uncertainties and challenges associated with the implementation of PtG in the biogas industry need to be assessed. The biogas sector is controversial in German society mainly due to its environmental and economic impacts and its critical safety deficiencies. Against this background, this thesis aims at analyzing how the German biogas chain could be transformed with the emergence of a PtG concept and at identifying approaches to efficiently tackle potential risks, uncertainties and challenges accompanying this renewable energy concept. The investigation draws on notions of risk perception and risk governance as a theoretical framework to identify and assess influential factors determining risk management for the implementation of PtG in the biogas sector and characterize essential requirements in the process of diffusion of the technology, its acceptance and legitimation. Following a random as well as a purposive sampling strategy, 27 experts representing key interest groups of the German biogas sector, i.e., industry, politics, research and associations, were interviewed face-to-face. Their perspectives on potential environmental, safety, sociopolitical and techno-economic risks and challenges that could hinder the implementation of PtG in the biogas value chain were systematically examined with the method of qualitative content analysis. With this technique, conclusions were derived based on a thorough scrutiny of the data collected. Overall, the participants of this study perceived a low risk of accidents, such as fires, explosions and environmental pollution, from biogas installations running with a PtG concept. They identified a lack of business models, missing political incentives as well as stigmatization of the sector as the main challenges in the adoption of PtG in the biogas sector. The stakeholders emphasized a knowledge gap in the general public to explain the low popularity of the biogas sector and its biobased products. In a successful deployment of this technological concept, the interviewees envisioned a replacement of farm-based biogas plants with fully industrialized facilities. The interviewed experts strongly emphasized the existence of regulations as the principal means to avoid potential technological risks.

The perception of the stakeholders corresponds with hierarchists as in the Cultural Theory of Risk. This mindset influences the way the experts recognize, manage and communicate risks. The participants prominently identified politicians as the primary accountable actors to handle risks, challenges and uncertainties of biogas associated with PtG. Although the media was broadly seen as a knowledge broker, the interviewees did not consider it as an instrument for effective risk communication to deal with distrust and stigmatization in the public and the controversies influencing the biogas sector, which could potentially affect the diffusion of PtG in the industry. The present study delivers key insights for the governance of the adoption of this technological concept in German society. In order to create a joint understanding among relevant stakeholders, facilitate informed decision-making and ultimately promote legitimacy for this technology, it is recommended to increase risk awareness among actors dealing with biogas and PtG. It is essential to foster deliberate communication among the multiple interest groups on diverging perceptions of risk and corresponding management options, so that an effective, accountable and participatory strategy to risk governance can be developed.

Keywords: Expert interview, biogas, PtG, risk governance, risk perception, cultural theory

Zusammenfassung

Die Verbindung von Power-to-Gas (PtG) mit Biogasanlagen zur Umwandlung überschüssigen Stroms aus erneuerbaren Energien in Biomethan stellt eine Innovation im Biogassektor dar. Dieses Konzept könnte zur Stabilisierung des deutschen Systems für erneuerbare Energien beitragen und die Biogas-Wertschöpfungskette sowie die daraus abgeleiteten Produkte wettbewerbsfähiger und umweltfreundlicher machen. Angesichts des wachsenden Interesses an dieser Technologie müssen potenzielle Risiken, Unsicherheiten und Herausforderungen im Zusammenhang mit der Einführung von PtG im Biogassektor bewertet werden. Der Biogassektor wird in der deutschen Öffentlichkeit hauptsächlich wegen ökologischer und wirtschaftlicher Argumente sowie Sicherheitsmängel kritisiert. Vor diesem Hintergrund soll in dieser Arbeit analysiert werden, wie sich die deutsche Biogaskette mit einem PtG-Konzept ergänzen lässt. Des Weiteren werden in der vorliegenden Arbeit potenzielle Risiken, Unsicherheiten und Herausforderungen identifiziert, die mit diesem Konzept einhergehen. Die vorliegende Untersuchung stützt sich auf Konzepte zu Risikowahrnehmung und Risiko-Governance als theoretischen Rahmen. Darüber sollen Einflussfaktoren bestimmt und bewertet werden, die das Risikomanagement für die Einführung von PtG im Biogassektor beeinflussen. Dies dient dazu, grundlegende Anforderungen zur Verbreitung der Technologie, ihrer Akzeptanz und Legitimation aufzuzeigen. Nach einer randomisierten sowie zielgerichteten Stichprobenstrategie wurden insgesamt 27 Experten aus zentralen Interessengruppen des deutschen Biogassektors, namentlich aus Industrie, Politik, Forschung und Verbänden, persönlich befragt. Ihre Perspektiven auf potenzielle ökologische, sicherheitsbezogene, sozialpolitische und technoökonomische Risiken, Unsicherheiten und Herausforderungen, welche die Einführung von PtG in der deutschen Biogas-Wertschöpfungskette behindern könnten, wurden mit der Methode der qualitativen Inhaltsanalyse systematisch untersucht. Die nach diesem Verfahren gesammelten Daten wurden eingehend analysiert und zu Schlussfolgerungen verdichtet. Insgesamt erachteten die Teilnehmer dieser Studie das Unfallrisiko z. B. aufgrund von Bränden, Explosionen und Umweltverschmutzung durch Biogasanlagen, die mit einem PtG-Konzept betrieben werden, als gering. Als Schlüsselherausforderungen bei der Einführung von PtG im Biogassektor haben die befragten Experten mangelnde Geschäftsmodelle, fehlende politische Anreize sowie eine Stigmatisierung des Sektors identifiziert.

Die Stakeholder verwiesen auf eine Wissenslücke in der breiten Öffentlichkeit, um die geringe Popularität des Biogas-sektors und seiner biobasierten Produkte zu erklären. Im Hinblick auf einen erfolgreichen Einsatz dieses technologischen Konzepts stellen sich die Befragten anstelle vieler Biogasanlagen auf Bauernhöfen vollständig industrialisierte Anlagen vor. Zur Vermeidung potenzieller technologischer Risiken verlassen sich die Stakeholder vornehmlich auf bestehende Richtlinien und Gesetze. Anhand ihrer Wahrnehmung lassen sich die befragten Experten nach der Kulturtheorie des Risikos als Hierarchen beschreiben. Ihre Denkweise beeinflusst die Art und Weise, wie die Stakeholder Risiken erkennen, steuern und kommunizieren. Die meisten Teilnehmer identifizierten Politiker als Hauptverantwortliche für den Umgang mit Risiken, Herausforderungen und Unsicherheiten von PtG im Zusammenhang mit Biogas. Obwohl die Medien allgemein als Wissensvermittler anerkannt wurden, betrachteten die Befragten sie nicht als Instrument für eine wirksame Risikokommunikation, um mit Misstrauen und Stigmatisierung in der Öffentlichkeit umzugehen und den Kontroversen im Biogassektor, welche die Verbreitung von PtG beeinflussen könnten, zu begegnen. Die vorliegende Studie liefert wichtige Erkenntnisse für die Steuerung der Einführung dieser Technologie in Deutschland. Um ein gemeinsames Verständnis unter den relevanten Stakeholdern zu schaffen, eine fundierte Entscheidungsfindung zu ermöglichen und letztendlich die Legitimität dieser Technologie zu fördern, wird empfohlen, das Risikobewusstsein der Akteure im Bereich Biogas und PtG zu erhöhen. Eine bewusste Kommunikation zwischen Interessengruppen bzgl. abweichender Risikowahrnehmungen und Bewirtschaftungsoptionen ist unerlässlich, damit eine wirksame, legitime und partizipative Strategie zur Risiko-Governance entwickelt werden kann.

Schlüsselwörter: Experteninterview, Biogas, PtG, Risiko-Governance, Risikowahrnehmung, Kulturtheorie

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Abbreviations

AEE	Agency for Renewable Energy
BM	Biological methanation
C.A.R.M.E.N.	Central Network for Marketing Agricultural Raw Material and Energy e.V.
CO_2	Chemical formula for carbon dioxide
CT	Cultural Theory of Risk
DBFZ	German Biomass Research Center gGmbH
DENA	German Energy Agency
EEA	European Environment Agency
EEG	Renewable Energy Sources Act
FNR	Agency of Renewable Resources
GHG	Greenhouse gas (es)
H_2	Chemical formula for hydrogen gas
IBBK	International Biogas and Bioenergy Centre of Competence
IINAS	International Institute for Sustainability
IRGC	International Risk Governance Council
LCA	Life cycle assessment
PP	Precautionary principle
PtC	Power-to-Chemicals
PtG	Power-to-Gas
RES	Renewable energy sources
SARF	Social Amplification Risk Framework
TÜV	Technical Inspection Association
UBA	German Federal Environment Agency
UMSICHT	Fraunhofer-Institute for Environmental, Safety and Energy Technology

Chapter 1. Introduction

1.1 Background

Driven by the interest of having abundant, reliable and more environmentally friendly energy sources, German authorities are facilitating the progress of renewable energy sources. The government enacted the Erneuerbare-Energien-Gesetz (EEG) – Renewable Energy Sources Act, on the 1st April of 2000 (Bundestag and Bundesrat, 2000), steering the growth of clean and modern power technologies throughout the country. This regulation was Initially called the Electricity Grid Feed Act, experiencing various changes since its ratification.

The German Energiewende – energy transition, is a political strategy that initiated in 1990 under political controversies, however gaining broad public and political endorsement since 2011, after the nuclear catastrophe in Fukushima. This energy transition in Germany aims at ceasing the use of nuclear and coal energy, in favor of renewable power by setting ambitious goals until mid of the current century. This strategy is centered on the following pillars: confront climate change, prevent against risks of atomic accidents, assure constant energy supply, while economic progress and attractiveness in domestic and international markets is maintained (Agora Energiewende et al., 2015).

The Energiewende leads the transformation of the German energy system, making it more sustainable and efficient while assuring its constancy. With this scheme, it is targeted to supply 80% of the power demanded in the country by 2050 from inexhaustible origins. Likewise, decision-makers thrive to make Germany carbon neutral by the same year, reducing its greenhouse gas (GHG) emissions by 80-95%, in contrast to values reached in 1990 (German Federal Cabinet, 2010).

To facilitate this energy transition, wind and photovoltaic power stations are being deployed, expanding their installed capacity across the country. However, these are volatile energy providers, as they are weather dependent technologies (Lauer and Thrän, 2017). By relying on several models and assuming an increment of renewable energy sources (RES), mostly from wind parks, surplus renewable electricity could reach between 1.1-13 TWh by 2020 in Germany (Stiller et al., 2010).

Further models reckon excess RES to be between 1.8-20 TWh in 2025 and 2040, correspondingly (Statista, 2018). Under these circumstances, concepts for power storage are being needed to balance the domestic energy supply.

Power-to-gas (PtG) represents a possibility for hoarding surplus renewable electricity in the form of biomethane (CH_4) in connection with a biological methanation process in biogas facilities. An electrolyzer assists in generating hydrogen (H_2), which is then combined with excess carbon dioxide (CO_2) obtained from various sources, e.g., exhausts from biogas processing. The combination of H_2 and CO_2 can occur through a biological methanation (BM) process in- or ex-situ biogas reactors, aided by archaea that metabolize both gases. With the increased supply of H_2, the generation of biomethane increases (Götz et al., 2016).

Following this process, the biogas sector could support stabilizing the electricity grid, providing renewable energy on a flexible basis. Methane is the principal component of biogas and in its chemical form constitutes a versatile means to hoard renewable energy. Due to its characteristics, biomethane can be conveniently deposited in the natural gas network or could be used for fuel cell transportation (Bucy; Collet et al., 2017; Götz et al., 2016).

Besides its energetic potential, biomethane can be employed as a platform substance for the elaboration of chemical products with added value, as a power-to-chemicals (PtC) concept (Bünger et al., 2017). From biomethane, several materials could be synthesized, e.g., methanol, ethylene and formaldehyde, which are of relevance for the chemical industry (Lunsford, 2000). An additional benefit of implementing PtG in this sector is that the biogas value chain could become greener, in which exhaust CO_2 could be recovered and re-used for the production of biomethane, attenuating this way GHG emissions when reactors are run alternately (Collet et al., 2017).

The PtG technology has high significance for balancing out the energy system, enhancing the productivity of the biogas industry and is in line with the political interest of expanding RES. However, the implementation of PtG in the biogas sector may embody substantial problematics in the form of risks to the environment and to human health, as well as challenges in the societal context in which is being developed, together with current technological and economic uncertainties.

The biogas sector on its own has been linked with multiple accidents and environmental pollution, situations which may endanger the acceptance and diffusion of a PtG concept associated with biogas. Some of the unfavorable examples in the biogas industry relate with blasts and flare-ups (Casson Moreno et al., 2016; Trávníček et al., 2018).

Besides, it has been associated with the discharge of digestate, microbiologically-rich and un-homogenized organic material into the environment (Keck et al., 2017; Kräft, 2015). Further criticism in the biogas technology has been directed to vast maize monocultures as a carbon source for its biological process (Pellmeyer, 2006).

The expansion of the biogas sector and its dependency on energy plants gave rise to significant transformations in agricultural markets, linked with the increased prices for food and land and to significant structural changes due to crop substitutions (Appel et al., 2016). This situation led to unfavorable prognostications as long as biogas/biomethane production relies merely on maize as main feedstock (Britz and Delzeit, 2013).

The prevalence of these topics in the media incited a discontent in German society and politicians systematically reduced and changed the format of their support to the field. Due to the growth the biogas sector exhibited, different from the societal expectations and the discourses leading its development, some authors suggest that the biogas technology has lost its legitimacy in the German context (Markard et al., 2016).

Some innovations can pose complex, uncertain and/or ambiguous risks, i.e., when the connection between the causes and effects of an event are not well-known, when there is restricted understanding on possible consequences, or when the nature of the occurrence leads to multiple considerations on its relevance or the reasons of its existence (Renn and Klinke, 2015).

In such cases, it is essential to analyze the attitudes of stakeholders involved in the progress of a technology, in order to evaluate their legitimate and normative discourses related with its development and adoption (Renn, 2015; Renn and Graham, 2006).Rosa et al. (2015) explained risk as “a situation or an event where something of human value (including humans themselves) is at stake and where the outcome is uncertain.”

In more detail, technological risk perception is considered as the judgment people make in light of specific evidence about possible detriments a technology could cause to objects, the ecosystem, the society or to economic organizations and their subsequent estimations on the likelihood and importance of such changes, consenting or refusing the proposed technology (Renn and Benighaus, 2013; Renn and Rohrmann, 2000).

Hall et al. (2014) and Köhler and Som (2014) emphasize on the relevance of considering the opinion of diverse stakeholders, particularly in the initial phases of development of a technology; when potential risks and impacts can be discussed and decisions are taken to direct its course of progress.

In this respect, the International Risk Governance Council (IRGC) explains the multiple advantages of integrating various stakeholders when dealing with the governance of risks. Some of these benefits are: i) to foster transparency in the application of measures for risk management; ii) impartiality and multiplicity, facilitating the contribution of various sectors; iii) efficacy and practicality in risk management, by collecting relevant feedback to handle risks in its societal context; and, iv) enabling a participatory and judicious platform for discussing and transferring relevant information on risk issues and thus improving risk management efforts (IRGC, 2018).

1.2 Aims and research questions

Multiple projects have contributed to understand stakeholders' attitudes towards the biogas industry in Germany and the energy transition (Emmann et al., 2013; Fischer et al., 2016; Kabasci et al., 2012; Markard et al., 2016; Schumacher and Schultmann, 2017; Stiehler et al., 2013; Theuvsen et al., 2012). Currently, PtG has been extensively investigated from a technical and economic perspective. Research in the field of stakeholders' perception of risks, benefits, challenges and uncertainties of PtG as an innovation part of the biogas sector is only in its beginnings.

From a scrutiny of the literature associated to this topic, the author encountered the study titled: "Livelihood Environment and its Security" from the state of Baden-Württemberg (research program BWPLUS) authored by Köppel et al. in 2017. That investigation comprised experts' opinions, investigating elements to facilitate the acceptance of PtG particularly within that region in Germany. However, the results were reported but not studied in light of any sociocultural theory.

In view of these knowledge gaps, the present study provides a comprehensive assessment of stakeholders' perception of risks, uncertainties, benefits and challenges linked with the adoption of PtG in the biogas industry. This investigation includes experts in biogas and the PtG technology, representing different key interest groups, stakeholders of biogas sector from throughout Germany, i.e., science, industry, politics and associations. As a result, this thesis aims at analyzing how the German biogas chain could be transformed with the emergence of a PtG concept and at identifying approaches to efficiently tackle potential risks, uncertainties and challenges accompanying this renewable energy concept.

In this investigation, the author integrates the notion of multi-stakeholder assessment of Gerkensmeier and Ratter (2018), assessing the contributions of individuals pertaining to diverse organizations related with or under the influence of an industry or activity, in this case the biogas sector, have a role deciding on its course of action or are explicitly in authority to influence its management.

The experts' judgment on potential environmental and safety risks, benefits and sociopolitical, economic and technological challenges of implementing the PtG technology into the biogas value chain were gathered and systematically analyzed in this study. Along with these aspects, the present investigation includes stakeholders' perceptions of using biomethane in an emerging biorefinery concept, which is of interest in the National Bioeconomy Strategy (BMEL, 2014).

This study goes beyond a technological and economic perspective, thereby analyzing the stakeholders' opinions with the lens of risk perception and risk governance theories. This approach allows to provide recommendations to decision-makers and interest groups on ways to deal with risks and uncertainties in the biogas sector and its innovation through PtG, in a comprehensive, participatory and resilient manner.

Ensuing research questions guided the development of this investigation:

- How do stakeholders of the German biogas industry characterize the kind of benefits that derive from implementing PtG into the biogas sector?
- What is their opinion concerning the novel use of biomethane as a platform substance in the chemical industry?
- In which way do the stakeholders perceive potential environmental and safety risks emerging from integrating PtG in biogas installations?

- What is their judgement concerning sociopolitical aspects that may challenge the diffusion and acceptance of PtG linked with the biogas production scheme? Subsequently, what do they believe triggered a decrease of public support in the biogas industry which could potentially influence PtG?
- Which technological and economic challenges do the stakeholders identify as essential tackling to facilitate the progress of PtG as part of the biogas industry?
- Which societal actors do the stakeholders consider are accountable to manage risks, challenges and uncertainties confronted in the implementation of PtG in biogas?
- Which measures do the interviewees conceive are vital for the management of identified risks, challenges and uncertainties?
- In which topics do the experts denote the most uncertainty about PtG as part of the biogas sector, hence requesting further investigation?

This study is of interest to researchers examining the potential of PtG in the German context and particularly to academics in the field of risk perception and risk governance research. The present investigation provides knowledge of how culture and the perception of experts in biogas are of relevance when managing and communicating risks and dealing with technological innovations.

Furthermore, the results of this research are of relevance to decision-makers and interest groups of the biogas industry, assisting them in a technological impact assessment of PtG in biogas, focusing on a stakeholder discursive evaluation. The present study provides recommendations for an effective, accountable and participatory strategy to risk governance for the biogas sector.

1.3 Structure of the thesis

This document is organized within seven sections, analytically describing the rationale, procedures, outcomes and main contributions of studying stakeholder perception of implementing PtG in the German biogas value chain. Below, there is a succinct explanation of the units composing this thesis. Figure 1 illustrates the association between each of these segments, connecting them stepwise and in a systematic manner.

Chapter 1: Introduction – In this section, the relevance of the research topic, its context and the scope of the investigation are concisely presented together with the research questions.

Chapter 2: Theoretical Framework – Essential elements of the conceptual background, namely, Theories of Risk Perception and Risk Governance are described under this segment. The author gives special attention to the following concepts: i) psychometric paradigm; ii) cultural theory of risk; iii) social amplification risk framework; iv) laypeople versus expert risk perception; and, v) the precautionary principle. Also, the overarching concepts of stakeholder participation in risk governance and risk perception of emerging technologies will be comprehensively discussed in this unit.

Chapter 3: Case Study – Essential features associated with the importance of biogas in Germany are described in this section. Furthermore, the notion of PtG in connection with the biogas industry and its relevance in the renewable energy system is concisely explained.

Chapter 4: Methodology – This section contains a detailed description and explanation of the reasoning behind the selection of the methodological approach followed in this research.

Chapter 5: Results – Main findings of the study are characterized in this chapter, including diagrams that summarize the content of the data obtained.

Chapter 6: Discussion – An in-depth analysis of the result's implications, relevance and association with the theories presented in chapter 2 are described in detail in section six. Encountered limitations and suggestions for further research complements the content of this section.

Chapter 7: Conclusions – This passage comprises the main contributions of this investigation in the fields of biogas and PtG, risk perception research and risk governance of bioenergy projects.

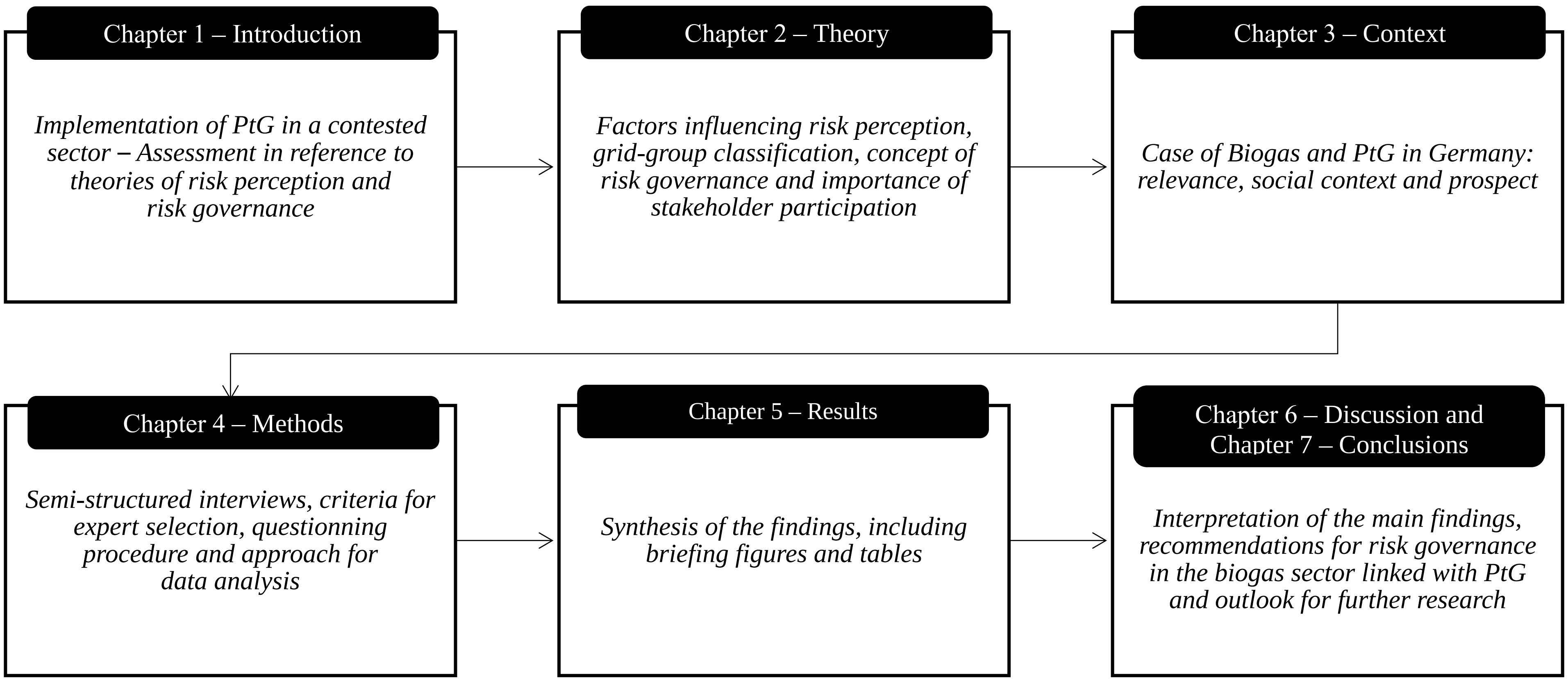


Figure 1. Outline of the structure and content of this investigation.

Chapter 2. Theoretical framework and relevant terms

2.1 Understanding risk, its governance and relevance in bioenergy

2.1.1 Defining risk perception and technological risks

The term risk has been interpreted in various forms, subject to the field in which is described and making it practical for the multifaceted matters dealt with, e.g., in engineering, management and finances (Aven, 2010). Diverse philosophical streams have emerged in social sciences, providing multiple explanations of risk. Lupton (1999) characterized the main postulates on the ontological notions of risk.

The first viewpoint is called "Realist", which depicts risks as objective events that can jeopardize people and materials. Under this philosophical field, risks can be quantified, detached from the influence of sociocultural aspects, but they are subject to public interpretations. This concept has been related to technical evaluation and management of risks. The second notion is termed "Weak Constructionist", which states that risks are real detrimental phenomena, inescapably appraised within sociocultural systems, thus can never be explained away from them. The third understanding on risk is the "Strong Constructionist", in which risks are manufactured from the influence of governmental, civic and traditional narratives (Lupton, 1999).

Niklas Luhmann proposed a concept of risk, in which the term is distanced from the notion of chance or predestination to an optative or "rational" decision mode emerging due to a modernization process occurring in contemporaneous groups. In a systems theory proposed by Luhmann, societies are conformed by various structures found in continuous communication, in which social risk disputes arise from shifting accountability of unfavorable consequences to other systems (Luhmann, 1993a, 1993b; Luhmann, 1991). Renn (2011) provides a typology of four central social systems, i.e., economy, politics, social relationships and culture. In Luhmann's systems theory, risk will be thus defined subject to the view, interests and values of reference from any of these social systems (Zinn, 2008).

Due to technological and environmental disasters, the notion of objectivity in risk-taking was questioned, retaking uncertainty in the analysis of risk. Evers and Nowotny (1987) proposed a differentiation between risk and danger, which was further expanded by Niklas Luhmann and Peter Japp.

It was explained that individuals, systems and objects are influenced by dangers [referred as natural catastrophes], while risks are potential detriments deliberately chosen by people in expectation of [economic] benefits (Evers and Nowotny, 1987). Throughout the literature, the concept of risk has been associated with an anticipated virtue, a likelihood, incertitude and as an incident (Aven and Renn, 2009). According to the International Risk Governance Center (IRGC) risk alludes to nonpredetermined effects an action could have and its potential disturbance on aspects of importance for humans (IRGC, 2017).

Current definitions of risk imply the following assumptions: (i) risk refers to a condition in which the consequences are not settled in advance; (ii) any outcome is hence highly uncertain; and (iii) something is in danger if it represents any worth to humans (Rosa et al., 2015). Aven and Renn (2010) argue that their interpretation of risk does not support complete subjectivism since social risk constructs can also be scientifically assessed; however, they emphasize that the judgment on the uncertainty and severity of outcomes lie on a person. This study was designed based on a novel definition of risk, postulated by Aven and Renn (2009, p. 6): *"Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value."*

Under the interpretation of Aven and Renn, risk includes a value judgment and has to do with what individuals perceive as relevant to them and what could harm or affect something they value (Rosa et al., 2015). Thus, risk becomes a normative term; besides, when confronted with risks, people discern on possible "states of the world" as consequences of risks, choosing an attitude towards them, which has important implications in decision-making and risk management (Aven and Renn, 2010).

Figure 2 provides a representation of this contemporary risk understanding, as proposed by Aven and Renn (2009). A phenomenon can cause certain effects, influenced by uncertainty. Both the event and the results of the impact are defined in reference to something of interest to humans, which defines its intensity or severity. In this illustration, the term risk is subject to people's awareness about its existence since its potential likelihood and dread effect can only be determined from a "mental construction" (Aven and Renn, 2010). Following this notion, risk perception has been explained as the discernment people do about risk, which is affected by information, e.g., observation, numerical assessments, means of communication and the own individual's cultural and psychological factors, such as feelings, predilections and character (Aven and Renn, 2010).

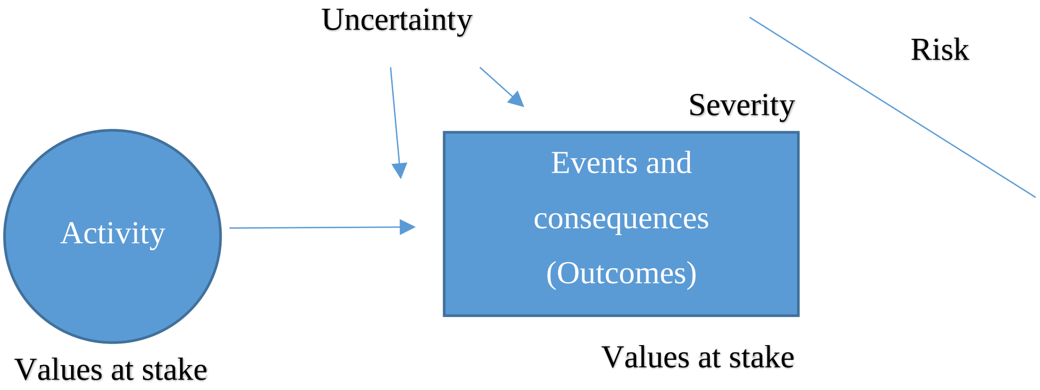


Figure 2. A modern interpretation of the term risk.

Source: Aven and Renn (2009).

The notion of risk perception received political attention in the 1960s, amid social revolts and controversies against nuclear power, which led to critical political consequences (Sjöberg, 2003). In the early development of this scientific field, the following issues were identified as essential to take into consideration understanding people's risk perception (Starr, 1969):

i) The assimilation of risk as a comparison among various sources of danger and the closeness or familiarity associated with it and

ii) The understanding that tolerance or acceptance of risks increased if people perceived benefits connected with the threat (a concept known as "voluntari-ness"). Cost-benefit-considerations were also part of this assessment.

As research in risk assessment continued, it was evident a gap between the public and experts since people were inclined to identify risks in areas where specialized groups categorized them to be safe (Sjöberg, 1999). The disagreement between experts and laypeople on risk perception and assessment was labeled as the "objective-perceived risk dichotomy" (Bostrom, 1997), increasing concern among both actors in decision-making and research.

In early studies on risk perception, the layman was portrayed as an "irrational individual" exaggerating fears, e.g., in the realm of environmental pollution, or lessening the relevance of health risks, e.g., not wearing a seat belt, which were perceived differently by experienced groups (Plough and Krimsky, 1987).

Expert knowledge was then deemed as objective and referred to for assessing what was considered “real” risks and not subjective ones (Slovic, 1997). This situation originated a systematic distrust among the general public and expert groups.

In this regard, there were arguments in the risk perception field suggesting that both experts and laypeople base their interpretations of what is a risk following different mental and social models (Wynne, 1992b). Besides, it was explained that in the risk society, expert knowledge is essential to obtain information and make conclusions on risks, however, it is not enough (Beck, 1992).

To understand both the nature of accidents and the legitimate acceptance and distribution of risks and benefits in society, risk identification and assessment has to incorporate the set of two: technical and social aspects of risks in a multi-disciplinary manner (Perrow, 1992; Renn, 1998b; Slovic, 1992; Starr and Whipple, 1980). Further details are provided on section 2.3 (“Laypeople versus expert risk assessment”).

Aven and Renn (2010) discuss the issue if risks are mental creations or real manifestations. First, they explain that risks arise from people’s reasoning of actual objects and events they perceive and undergo in their environment. Their view on risk as “mental construction” implies that people assign meaning to what is a risk. They explain that with time, social groups gain experience on their understanding of risk and thus, discriminate between what is relevant as threatening and what could be instead be regarded as not fearful (Aven and Renn, 2010).

Discerning on risks within a society or in an organization follows a methodical process influenced by cultural ideologies, e.g., a shared conviction that people’s lives must be safeguarded; by corporate, organizational and/or economic interests, e.g., what is worth investing in; and by organized knowledge, e.g., applying statistical models to assess probability and severity of events to occur (Aven and Renn, 2010).

Regarding innovations, Renn and Benighaus (2013, p. 295) reviewed from the literature that technological risk perception can be interpreted as:

“The processing of physical signals and information about potential hazards and risks associated with a technology and the formation of a judgment about seriousness, likelihood and acceptability of this technology.”

Renn and Benighaus (2013) adapted a comprehensive model connecting known theories of risk, which were developed over the last 50 years, namely, psychological, social and cultural factors influencing people's risk perception. This model was initially elaborated by Renn and Rohrmann (2000). Figure 3 shows this schema, containing the principal influencing factors in people's risk perception, structuring them into four sequential stages.

Level 1: Heuristics

On this point, people form their risk perceptions based on the conclusions they make from their daily lives and routines. The typical "trial and error approach" assists people to form their attitudes and is the denominated "common sense" technique, which may originate from the individual or the society (Renn and Benighaus, 2013).

Level 2: Cognition and Affections

These two elements influence how people perceive the characteristics of certain risks. Cognition includes what people believe is right about a risk, assigning qualities to them, depending on their level of familiarity with the fearful event or activity. Similarly, emotions play a role in risk perceptions. Feeling good or bad, this interferes with people's attitudes towards risks (Renn and Benighaus, 2013).

Level 3: Social and Political Structure

This stage refers to regulating institutions and how people associate to them. Trust in such institutions is an essential aspect understanding risk perception since it influences how they accept risk information and from whom to form their opinions on risk. Also, people's socio-economic status, roles in society and political affiliations determine the mindset people form towards risks; so does the media and recurring groups influence their risk opinions (Renn and Benighaus, 2013).

Level 4: Cultural Organization

This stage is based on the described termed cultural theory of risk, in which people's rationalities towards risks are based on their grid/group arrangements. People's opinion concerning risks is not about the characteristic of the risks in themselves, but on their worldviews, their social cohesion and ideologies (Renn and Benighaus, 2013).

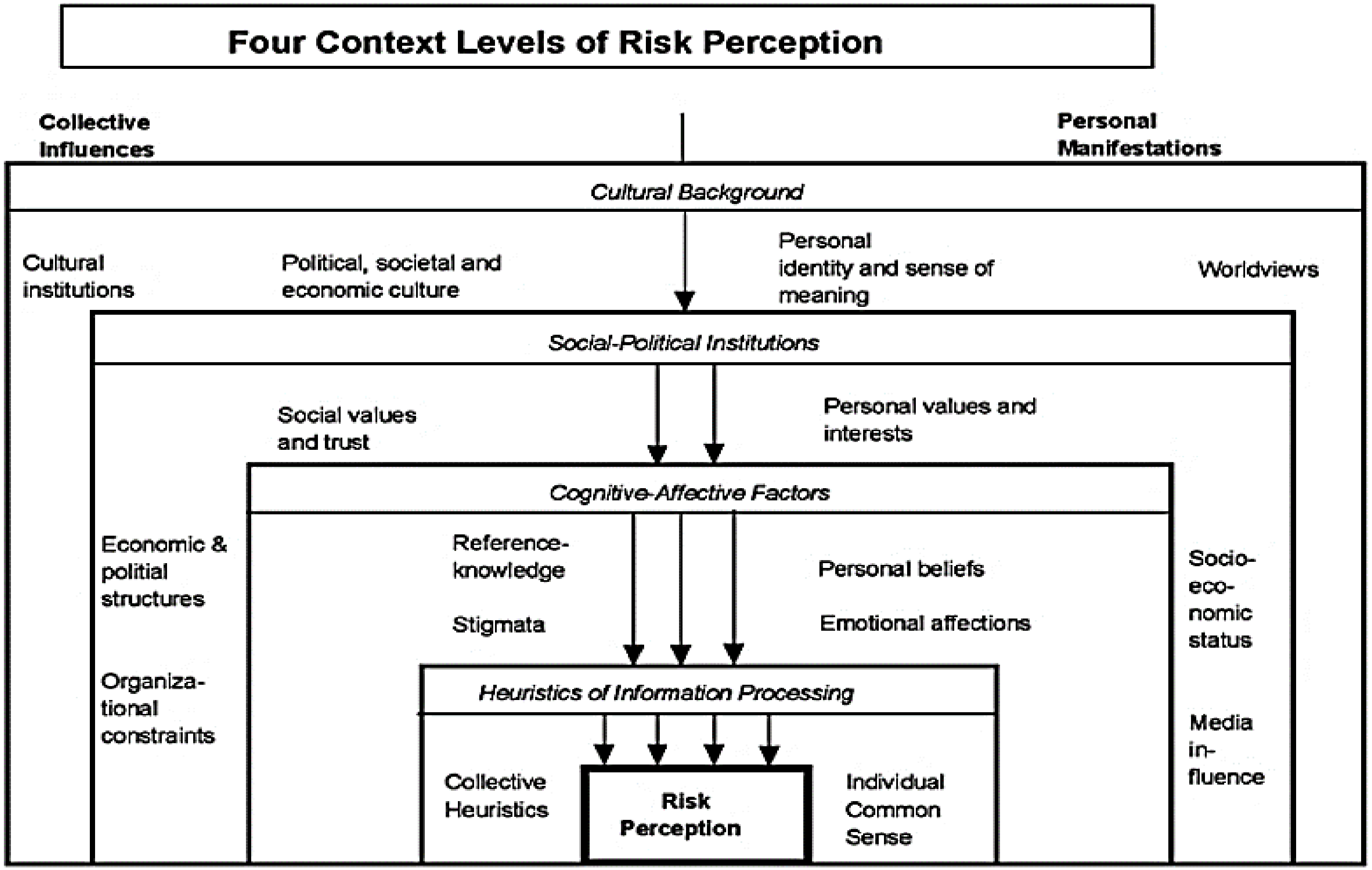


Figure 3. Sythesis of the main factors influencing risk perception.

Source: Renn and Rohrmann (2000).

2.1.2 Explaining risk governance

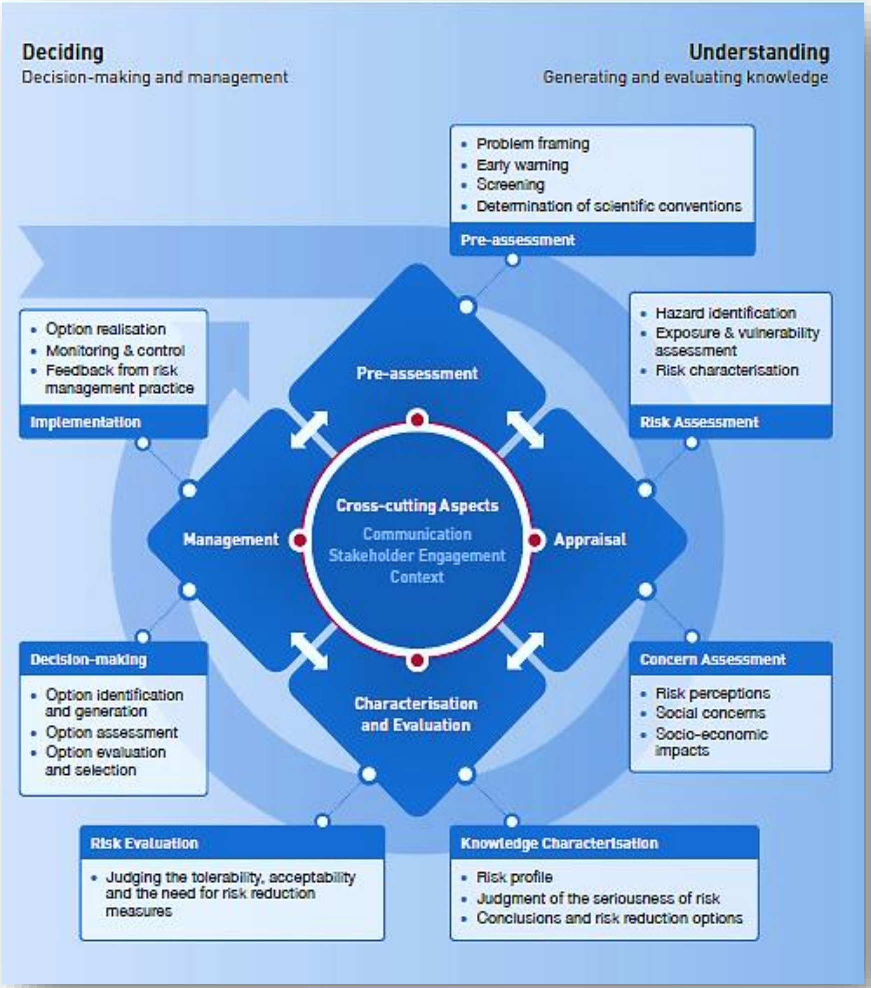
Dealing with multifaceted, unclear and controversial risks tends to cause social unrest and represent significant challenges to risk agents and institutions. Risk management organizations and decision-makers require strategic approaches to handle such risks. This risk control is possible by incorporating technical knowledge and following political structures while considering people's values and interests to achieve legitimate and efficient solutions (Renn and Klinke, 2015). Risk Governance is a concept that integrates organizations, its mechanisms, structures and culture to manage risk information and take pertinent and collectively approved decisions to handle risks (IRGC, 2017).

Risk governance includes aspects such as how vital risk information is gathered, studied, interpreted and communicated. It refers to descriptive and normative elements, leading to the concepts of good governance by aiming at, among others, clearness of work, appropriate use of resources, sustainability, justice, compliance to the law and accountability (IRGC, 2017). The notion of governance in risk management advocates that influence on decision-making and access to information should be uniformly distributed, allowing the incidence of various actor-networks. In this manner, diverse interests, roles and relationships among social groups are represented (Renn et al., 2011).

The IRGC's Risk Governance Framework is a widely accepted approach for incorporating various areas of expertise and various stakeholders in the risk governance process. Figure 4 depicts all the different elements that compose this concept. In the following sections, each of these stages is described in detail. This framework has been developed to increase resilience in societal systems, by strengthening the capacity to deal with unintended effects, lack of knowledge in the presence of risks and potential societal conflicts (IRGC, 2017).

The IRGC framework is developed on the basis that risks should be handled based on the local conditions of the affected societal group. This notion includes the consideration of inherent governing and working cultures in communities, especially regarding how risks are handled and communicated and the conditions of the period in which they are being managed since risk problems and solving strategies change over time. Communication is a process that is part of the whole risk governance mechanism and considers the integration of all relevant stakeholders (IRGC, 2017); further details are provided in the following subsections.

a)



b)

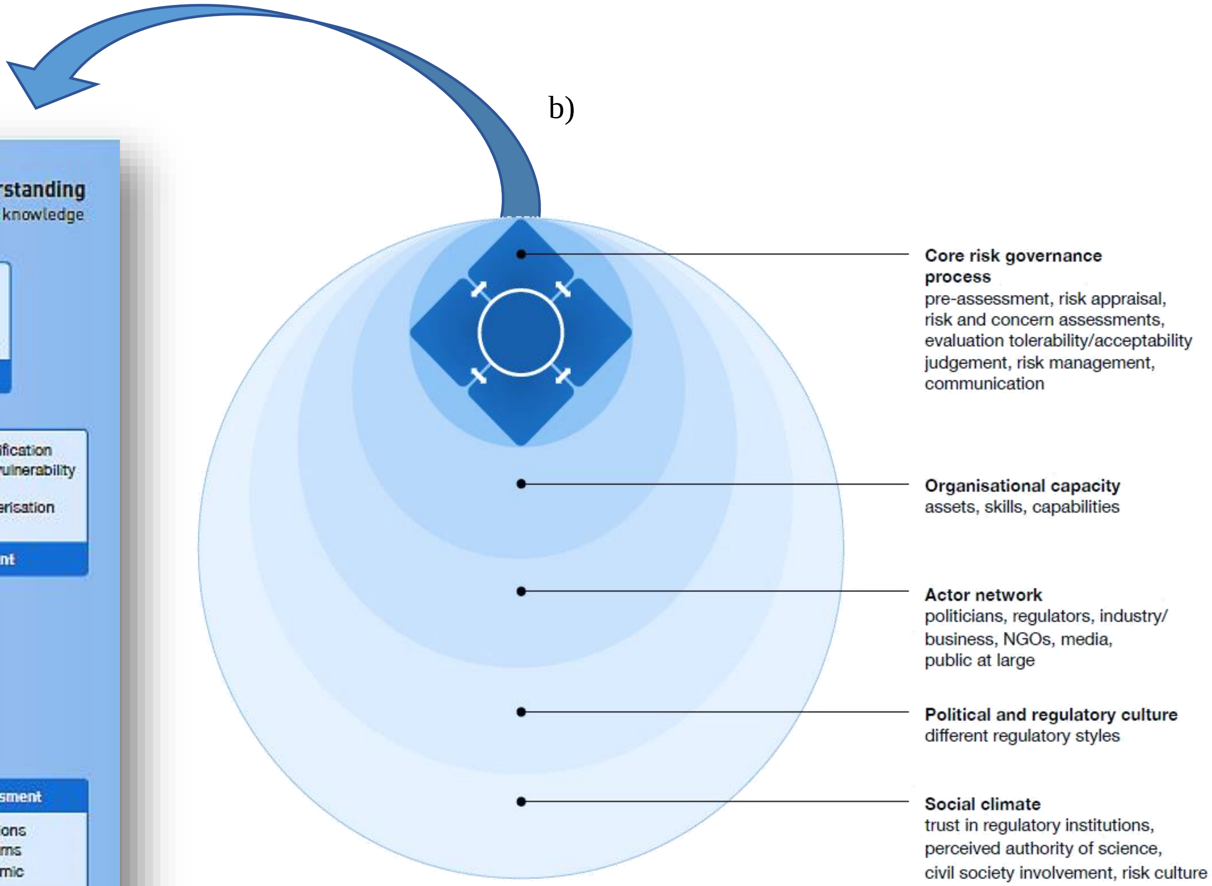


Figure 4. Elements and process of risk governance (a) and its global context (b).

Source: IRGC (2017).

Pre-Assessment

In the consideration of risks as socially constructed understandings of a threat (Aven and Renn, 2010), a pre-assessment is the initial step in which the risk issue is conceptualized. People's standpoints and beliefs are gathered on the matter and scope of the risk problem, here is also identified if any regulation or procedure would be pertinent (IRGC, 2017).

In this stage, the risk issue is formulated and characterized. It serves as a first review on the troubling subject, considering affected actors and groups, assessing their different understandings on the problem, their concerns, interests and opinions on how to handle the risks (IRGC, 2017).

During the pre-assessment step the different angles linked to a risk situation are analyzed, delineating the parameters that guide the further stages: evaluation and control. Doing a pre-estimation of risks assists with:

(i) Clarifying what a specific group considers as dreadful but also, what is perceived as beneficial, resulting from the risky activity or situation;

(ii) Identifying any risk evidence, habits and structures in a community or society, that help label something as a risk; and

(iii) Gaining awareness on how society understands risks should be handled, this leads to the legitimacy of the problem and ultimately, its solution (IRGC, 2017).

Sample questions in the risk pre-assessment stage are (IRGC, 2017):

- Which risks and benefits are being tackled?
- Who should be considered as a stakeholder? How do they influence the understanding of risk in a community or societal group?
- What are the bureaucratic structures and relationships among the different actors?
- How does the risk issue influence different people? Does it generate any campaign in society?
- Which systems are influenced by the risk issue: economics, politics, societal structure, or the environment?
- Which limitations should be considered in planning any risk management?

Appraisal

A systematic and comprehensive evaluation of the risk in question is performed on this phase. This analysis refers not exclusively to collecting technical information about the risk object or event, but also about its financial and societal effects. The risk appraisal thus includes the assessment of attitudes and fears of a community, in relation to potential threats. Both perceived and measured cause-effects relationships are studied in this phase (IRGC, 2017; Renn, 2008). The risk appraisal should be interdisciplinary, including methodological evaluations of risks to people's wellbeing (associated with their health, environment) and the social consequences; integrating this way, people's perceptions of risks (Renn and Walker, 2008).

According to Klinke and Renn (2012), this wide-ranging evaluation is composed of two parts: (1) Risk assessment, in which specialists from technical fields of research measure probabilities and severities of potential threats, generating estimations of their analysis; and (2) Concern assessment: specialists employ methods from social sciences to determine the level of risk concern in a society. Some of these methodologies include among others surveys, focus groups and interviews.

The results from these assessments show a characterization of risks, based on the following criteria: (i) kind of harm, (ii) likelihood of the event to happen, (iii) level of uncertainty, (iv) scope or extent of damages, (v) duration, (vi) discontinuity, (vii) latency and (viii) dissemination, succeeding in societal distress, such as injustice, disputes and cascade effects in other sectors or systems (Renn et al., 2011; Renn and Klinke, 2015).

Some of the questions that integrate a risk assessment include (IRGC, 2017):

- What kind of damages could result from the handled risk? What is the resilience level of the affected communities/ societal groups?
- Which models could be generated that help assess the risk likelihood and impact?
- How feasible is the quantification of the risk matter and how reliable are the models?
- What are the multi-stakeholders' perspectives on the risk matter? What kind of factors may affect their risk perceptions?
- How do people react to the risk issue? How are the social institutions arranged?
- What is the resilience potential of risk management institutions and agents?

Risk Characterization and Evaluation

This stage helps to classify risks based on the knowledge that was gathered about them. Risks can then be categorized as: simple, complex, uncertain, ambiguous or a merger between them. In this stage, a decision regarding the risk seriousness and urgency is taken, leading to the control of the matter at hand (IRGC, 2017).

Simple risks are identified when a clear cause-effect relationship between the trigger and the consequences are drawn (e.g., car accident). Decisions on risk management are conventional, making a cost-benefit analysis of the measures and the outcomes (IRGC, 2017; Renn and Klinke, 2015). When risk issues are intricate, more refined solutions are needed and diverse stakeholders must take part in the evaluation, characterization and decision-making on risks (IRGC, 2017).

Complexity emerges when the linkage between a broad range of possible causes and consequences cannot be traced and determined (Underdal, 2010). There are no linear relationships. However, specific models can assist assess the probability of damage and the factors that generate or accentuate an effect (Renn and Klinke, 2015).

Uncertainty exists when the event cannot be explained with available scientific knowledge, or the existing data is not sufficient to characterize the threat, although even at the existence of evidence, ambiguities and controversies commonly arise. Additionally, human knowledge is limited and selective, thus, it is prone to indeterminacy in its predictions and conclusions (Laudan, 1984; Renn and Klinke, 2015).

One refers to ambiguity, when people have diverging normative or interpretative perspectives on the nature of risks, leading to conflicts (IRGC, 2017). Interpretative ambiguity means that there are different (legitimate) understandings of an equal source of information (IRGC, 2017).

Normative ambiguity refers to the different preferences people have as to accept certain consequences, based on their lifestyles, quality of life, ethics and their attitudes towards the distribution of risks and benefits. More importantly, most risks are described as a mixture of all these attributes (Renn and Klinke, 2015).

Risk Management

Once the predominant risk attributes have been studied, decision-makers can study risk problems and make better-informed decisions to avoid potentially controversial consequences and mitigate such threats, as part of a risk governance mechanism. In risk management, decision-makers deliberate in a legitimate way on a risk control strategy (IRGC, 2017). When risks are tolerated, it is necessary to implement measures to help maximize the benefits obtained from an activity, while potential threats are being avoided or mitigated to promote an adaptation to the consequences (IRGC, 2017; Renn and Klinke, 2015).

Figure 5 shows a conglomerate of available strategies to tackle risks based on their characterization. When handling (i) simple risks: conventional control mechanisms can be used, such as regulations; (ii) complex risks: the best available technology and knowledge is selected and usually requires the intermediation of experts (risk-informed control) to achieve sound approaches to reduce negative impacts of risks; (iii) uncertain risks can be managed either with a) precautionary principles (when effects are highly loaded with uncertainty, cf. 2.5) or b) resilience mechanisms, reducing vulnerability and/or strengthening the capacity of any system or groups after any undesired consequences; (iv) ambiguous risks involve all relevant stakeholders to take a decision to manage risks and benefits. The aim is to understand people's narratives towards risks, increase tolerance and societal cohesion (IRGC, 2017).

A central element in risk governance is the communication among all actors involved in the management of risks. The IRGC's risk governance model reinforces the relevance of communication among diverse social groups that are impacted by a risk. This concept is interpreted not as merely sharing information about risks and its management strategy, but as the integration of relevant stakeholders throughout the whole design, management and evaluation process of the risk governance scheme. Their participation in the risk assessment model is conceived for both, in the process of risk evaluation and during risk characterization. This way, stakeholders participate in risk decision making and management (IRGC, 2017). Figure 6 provides guidance in the integration of different stakeholders as a function of the type of risks being handled, namely complex, uncertain or ambiguous. Typically, risks are a combination of different characteristics. Thus, it is expected the engagement of multiple and diverse stakeholders during risk consultations.

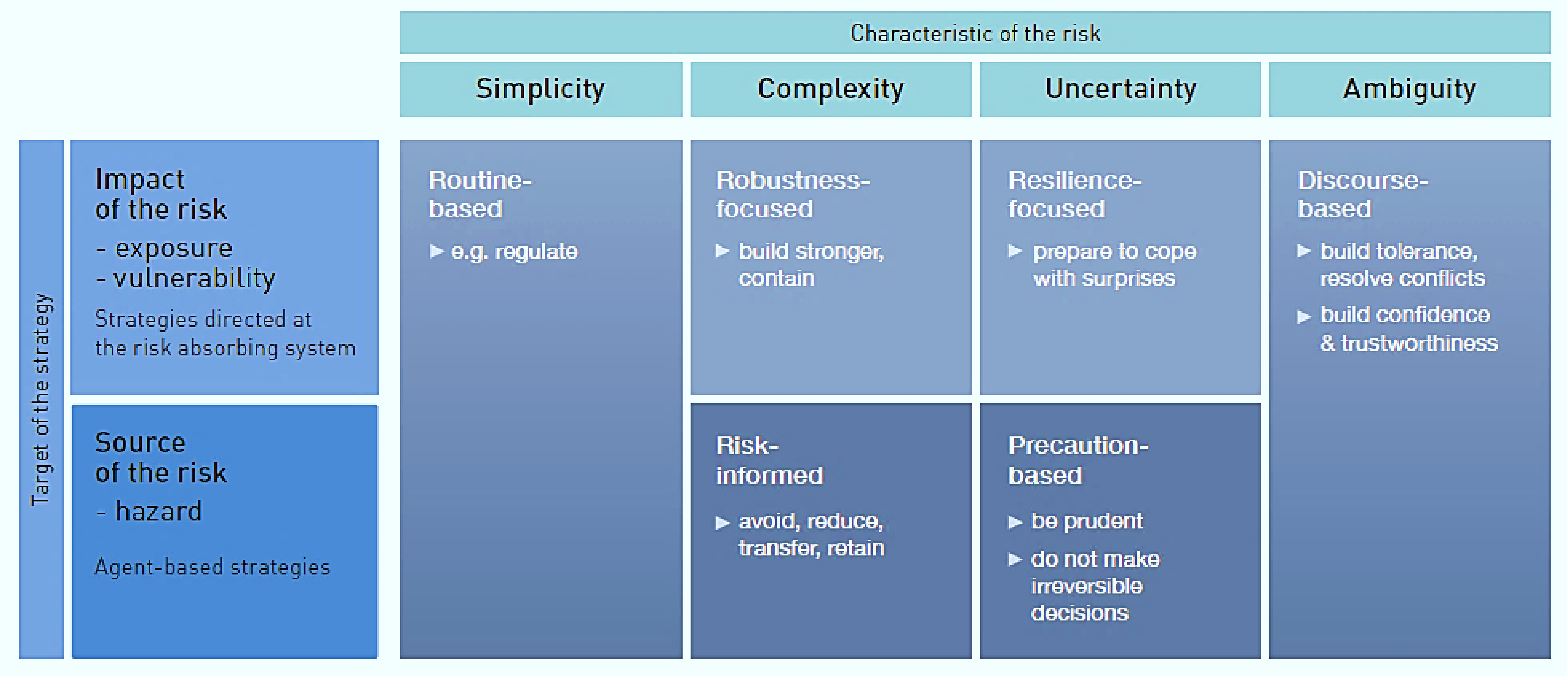


Figure 5. Approaches for risk management as a function of the risk characteristics.

Source: IRGC (2017).

Risk Communication and Stakeholder Engagement

Having a good communication among all interest groups is essential to achieve an effective and efficient risk governance. This aspect should be maintained throughout the process aiming at managing risks. Risk communication assists both for internal risk governance processes, with risk managers, as well as for external ones, dealing with the public and affected stakeholders (IRGC, 2017). Internally, risk administrators can state a shared comprehension on their duties; externally, it helps to promote awareness in people on arguments of risk managers for choosing a particular risk control strategy (IRGC, 2017).

Stakeholder communication is an essential element in risk governance since it facilitates building effective partnerships among all interest groups. Information on the stakeholders, their priorities, moral standards and ideologies can be integrated into the governance mechanism, which makes risk management more effective and resilient (Renn, 2015). Besides, by successfully communicating with relevant groups, as part of a risk governance scheme, stakeholders could become direct promotors of the results and approaches of the implemented risk measures (Renn, 2015).

Aven and Renn (2010) outlined four goals that are achieved by transferring information to stakeholders on risk management and by integrating them in the risk governance process. The primary purposes of a risk communication strategy are to (Aven and Renn, 2010):

i) Promote awareness on the various risk perceptions prevailing in society among various interest groups, e.g., business members, public, decision-makers, organizations (“enlightenment function”).

ii) Facilitate a transition to different conduct among people, targeted at minimizing the vulnerability towards risks and mitigating potential effects (“behavioral change function”).

iii) Increase acceptability and reliability in institutions and those responsible for managing risks (“trust-building function”).

iv) To enable the exchange of ideas among stakeholders about controversial topics concerning risks, to identify practical means to handle risks, to solve disputes and to provide a platform for egalitarian design and control of risks (“participatory function”).

According to the IRGC, besides an engineering-based risk assessment, a "concern-assessment" should be incorporated in a risk governance process, which enriches the decision-making and optimizes the outcomes of a risk management approach. In a concern assessment, topic troubling relevant interest groups are assessed, based on how those stakeholders conceive the level of seriousness of a risk and its possible consequences (IRGC, 2017).

The following questions are applicable when designing a risk communication strategy (IRGC, 2017): Which structure could be followed to ease the communication among stakeholders? What type of content is required from the different interest groups? Is there any stakeholder that could ease the diffusion risk information? What knowledge about risks is available? Does the communication strategy consider how risks are perceived?

Various techniques have been identified, to facilitate the integration of various social groups in the risk governance process. Figure 6 illustrates key mechanisms to engage diverse stakeholders in risk governance, according to the main risk features. Following paragraphs outline the core methods for stakeholders' participation in risk governance (Renn and Klinke, 2015):

- **Instrumental approach:** This technique is selected when one deals with simple risks. Statistical analyses provide enough information about the problem at hand. These risks can usually be handled with regulations, considering cost-benefit assessments to support political instruments.
- **Epistemic approach:** In this type of participation, existing knowledge is examined and deliberation among different experts is pursued. The cause-effect relationships that lead to risk are explained, to help characterize threats and understand potential consequences. An interdisciplinary scientific community is best suited, including both natural and social sciences.
- **Reflective method:** The aim is to find a general agreement among various stakeholders, finding a middle point in which specific risks can be tolerated at the exchange of benefits. With this technique, one deals with argumentations on risk managing capacity and compensation mechanisms.
- **Participative engagement:** In case of controversies, the public and all relevant stakeholders should be involved, to widely discuss the risk matter. The aim is to find common values and ways to cope with risks without disturbing many lifestyles.

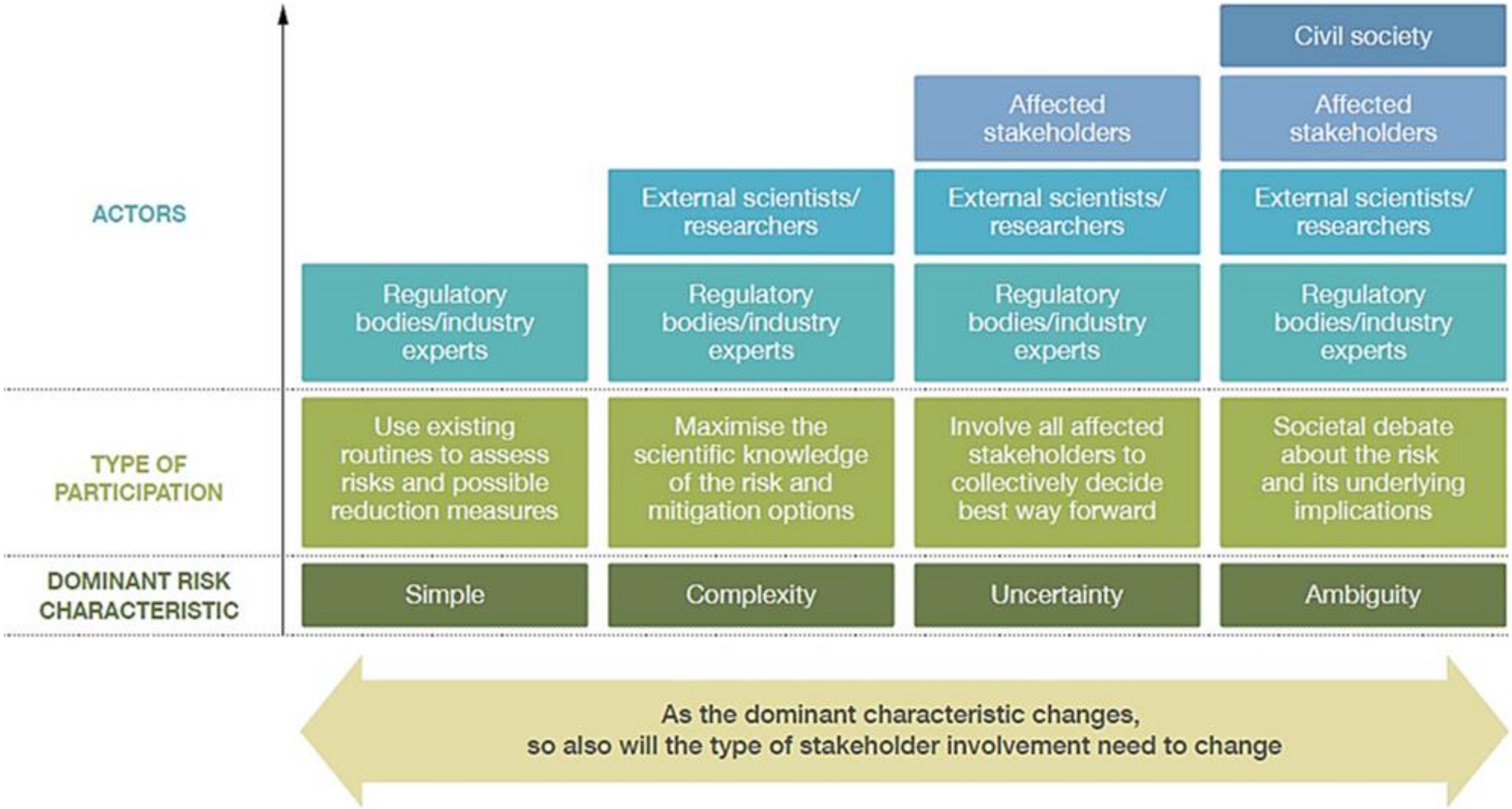


Figure 6. Stakeholder participation subject to main risk characteristic.

Source: IRGC (2017).

Renn (2015) proposed the following models as integrative options when assessing risks characterized by a combination of complexity, uncertainty and ambiguity:

- **Design discourse:** This concept is referred to when various of the previously described methods and sub-formats are used to identify options for risk management. Choosing any of the individual approaches is subject to the kind of risk problem, the social setting and its governmental and ideological characteristics.
- **Cooperative discourse:** this approach aggregates in a consistent form three of the available participatory approaches. The first stage aims at defining the purpose of the risk assessment with the participation of pertinent and diverse stakeholders. They then express their understandings, values, interests and their preferred benchmark to evaluate the proposed methods for handling risks (reflective discourse). This phase is then followed by an assessment with specialists in a transdisciplinary form (epistemic discourse). The process is then concluded by letting a social group or various of them, e.g., randomly selected individuals, to assess the different options (participatory model). A panel composed by chief stakeholders, e.g., decision-makers and sociocultural leaders, review the contributions and draft a report with conclusions.

2.1.3 Risk governance of bioenergy projects

In seeking to reduce production costs and assure a sovereign provision of efficient and environmentally friendly energy sources, decision makers are commonly motivated to promote technologies in the renewable energy sector (IRGC, 2007).

Bioenergy is a green energy form, known to offer multiple benefits in modern energy mixes, among them (IRGC, 2007):

i) Fewer carbon emissions in contrast to conventional fossil fuels;

ii) Promoting local energy generation, attenuating dependency on foreign energy supply and broadening the national energy portfolio;

iii) Supporting governments in the achievement of domestic clean energy targets while supplying the required energy for economic growth at reasonable prices;

iv) Facilitating the participation of biomass-based energy producers in the energy market, thus, providing jobs in rural areas; and

v) Helping reduce organic waste, which energy content is otherwise discarded.

Bioenergy can find multiple uses, for example, in the generation of biofuels, heat, electricity, or a combination of the latter (IRGC, 2008). Despite these manifold benefits, the generation of energy from biomass is confronted with severe risks of environmental, social and economic nature (IRGC, 2007; Thornley and Gilbert, 2013).

These authors have listed the following environmental risks: i) ecosystems could be mismanaged; ii) water bodies could be contaminated, influencing its quality and availability; iii) decrease of the restorative potential of soils; iv) associated land use changes with multiple indirect effects; and v) emission of air contaminants (IRGC, 2007; Thornley and Gilbert, 2013).

Social risks include i) potential controversies due to the negative public perception of bioenergy; and ii) in some regions, food security and land rights are topics of dispute. Regarding economic risks, one can mention: i) indirect impact on food prices; and ii) inefficient production model through subsidies, leading to a suboptimal energy market (IRGC, 2007; Thornley and Gilbert, 2013).

Other risks arising from bioenergy generation are associated with potential transformations of the scenery, in conflict with interests and the culture of local communities; possible use of genetically engineered microorganisms when bioenergy producers seek options to increase their energy yields; potential of regional structural changes due to unsustainable use of natural resources, which may lead to potential conflicts in the management of land (Lewandowski and Faaij, 2006).

When dealing with risks and benefits of energy obtained from biomass, decision makers are confronted with multiple governance challenges, as Purkus et al. (2012) explain. These conflicts are present throughout the whole value chain of bioenergy projects in which the existence of alternatives makes the decision-making process more complex (Purkus et al., 2012); and thus, requiring the intervention of multiple stakeholders.

Governance challenges of bioenergy arise from the feedstock generation, to the biological transformation into energy and to the energy supply and final use in society (Purkus et al., 2012). The following governance problems may arise in the process of bioenergy generation:

i) Opposing interests in land use, its management and cultivation techniques;
ii) Undecisiveness on optimal locations for sourcing biomass;

iii) Finding alternatives on the use of biomass, e.g., energy vs. food;

iv) Choosing among various conversion technologies and dilemmas due to multiple utilization pathways of energy.

Several authors have provided recommendations to govern these complex issues in conventional bioenergy production. Among their solutions is the creation of a “bio-energy labeling organization (BLO)” and a “United Nations Agreement on Bio-energy (UNAB)” (Verdonk et al., 2007). Others have offered insights on the identification and analyses of various political schemes under a “neo-liberal” or lax regulation; a profit-led state or a socially responsible archetype (Midttun, 1999).

On this matter, the International Risk Governance Council (IRGC) provided various principles to assist decision-makers from business and politics to deal with governance risks of bioenergy projects. These recommendations include (Florin and Bunting, 2009): generation of better estimations on energy potential from biomass; improvement of land-use policies to optimize its use; promote better cultivation techniques among producers; advocating for bioenergy technologies based on waste as input material; implement exhaustive risk appraisal techniques, considering regional stakeholders; and offer reliable information to the public.

More recently, Stern (2011) suggested to endorse technological research in consideration of its potential risks to aspects of human value; make available the engagement of interest and influenced groups both in the assessment and management of risks, thus making the risk appraisal more participative and transparent and involve governing organizations in the process. Sidortsov (2014) urged to deal with risks, not as a numerical data processed independently of its context since its social scope is vital for risk management.

Due to the discussed risks of bioenergy production, decision-makers have been urged to support mechanisms and technologies of the bioenergy sector, which are run with waste instead of energy crops. At the European level, there is for example, strong interest to promote the use of waste from the food and beverages industry in biogas production, increase awareness among relevant stakeholders about the potential of using food and agricultural waste in the energy generation and support in the transfer of best techniques (European Commission, 2014).

2.2 Theories on risk perception

The following subsections render an overview of principal theories of risk perception research, serving as a framework for the analysis of the results obtained in this investigation. Various explanatory notions have been proposed as for how and why different societal groups perceive technological and environmental risks in a particular manner. The present study aims at applying the fundamental concepts of risk perception research for the understanding of possible factors that influence interviewed stakeholders of the biogas sector to exhibit a distinct attitude towards safety, environmental, economic, technological and reputational risks associated with the implementation of PtG in their field.

These theories are structured in such a manner to first, provide an understanding of the role of affection and emotions on the formation of risk perception in individuals, as explained by the psychometric paradigm. Second, to explain how worldviews and cultural predispositions regulate people's responses to risks. Third, to describe the mechanisms in which risk messages and signals are transferred among societal actors and/or stations and an explanation of the secondary effects of risk amplification, including potential technology stigmatization. Moreover, the precautionary principle is introduced as a practical notion for dealing with the risks of emerging technologies and the uncertainties they entail.

2.2.1 Psychometric paradigm

This notion constituted the commencement of social science risk research and stated that affection and emotions influence how people form their attitudes towards risks. The psychometric paradigm is essentially a cognitive theory, but besides considering risk as a discernment about threats, it also integrates worry and concern about potentially unfavorable consequences. This preoccupation is then reflected on the intensity and the seek for means to mitigate risks and its potential outcomes (Sjöberg et al., 2004).

This theory has been the most influential one in the study of risk perception (Slovic, 1992). It indicates that judgment on risk is determined by diverse psychological aspects, which can be numerically appraised and ranked, depicting the nature of the risk issue (Fischhoff et al., 1978).

In the characterization of a risk phenomenon that individuals consider when forming their risk perception, nine features have been distinguished to be exceptionally relevant (Fischhoff et al., 1978; Gray and Ropeik, 2002; Ropeik, 2004; Rundmo and Nordfjærn, 2017; Slovic et al., 1974):

- Deliberate exposure to risk (“voluntariness”): The less freedom people have to select the risks they are exposed to, the less tolerability they pose to them.
- Trust: When people are confident about the institutions and stakeholders responsible for managing and communicating on risks, the more people accept risks.
- Fear (“dread”): People are more frightened to those risks that may kill them in a horrifying than in a gentle way.
- Cataclysmic or abiding: This theory provides evidence that people are more afraid of risks capable of killing a large number of people in a single event and an exact place than deadly progressive risks that kill people in dispersed sites.
- Command or “control”: If people feel they can regulate the course of risk or the process that generates it, they fear less its potential consequences.
- Origin of the risk “anthropogenic or biogenic”: When the emergence of risk is due to human influence, people show more anxiety than nature-derived risks.
- Incertitude or “uncertainty”: In the existence of ambiguity about the potential consequences of a technology or an event, people tend to be precautional and more anxious.
- Familiarity or “newness”: Investigations in the risk perception field have indicated that the longer people are accustomed to risk, the less fear they develop towards it and vice versa. Once people have experienced the consequences of a risk issue and have built an understanding on the scope of danger, they build mental models that help them calculate the level of tolerability they would exercise to the risk at hand.
- Knowledge about the risk, “awareness” or availability: The more conscious people are about a risk, e.g., due to intense media coverage, the higher fear people pose to a sole risk, independent of its probability to occur or severity.

Other attributes of risks influencing people’s perception include (Ropeik, 2004): the capacity of the risk consequences to impact future generations, e.g., children, is perceived as highly dreadful. Besides, if a risk is perceived to be personal, e.g., from a statistical result of 1 in a million that individuals or someone they care about is influenced, then the level of rejection of the risk source is higher; finally, if people see a benefit in a risk, its acceptance increases.

The level of education is also a parameter that has been identified as influential in the way people perceive risks. Risks are assessed to be less threatening, the higher the level of education of an individual since they may be aware of safety mechanisms of keeping risks under control (Kraus et al., 1992). In a similar approach, Rundmo and Moen found in their study in 2006 that experts have a lower risk perception than lay people and politicians, focusing more on the probability of occurrence of a risk event. Chapter 2.3 provides details on reported differences between expert and laypeople in risk perception. Moral also plays a role in risk perception. Sjöberg and Winroth found in 1986 that morality behind risk actions was an influencing factor in the acceptability of risks.

Under the psychometric paradigm, it is understood that the media has a strong influence on people's attitudes toward risks and the characteristics they assign to them (Rundmo and Nordfjærn, 2017). Another theory has been developed explaining in detail the social process of risk amplification (cf. 2.2.3). Results from the psychometric paradigm have provided valuable recommendations to how decision makers and risk managers should inform people about risks, including how they present information in the media. Ropeik (2004) suggests that risk communication has a less impact when decisions informed to the public are not obtained in dialogue with potentially affected stakeholders.

Moreover, understanding of the aspects influencing risk perception from the psychometric perspective provides evidence to risk communicators on the need to accept and respect people's worries towards risks. For an influential risk communication, decision-makers need to deliver messages in consideration of the psychological and emotional elements influencing the public on their perceptions and in a tone that is compatible to the affection and their expectations, in order to build trust and acceptance of risk information provided (Ropeik, 2004). The psychometric paradigm has been described as a cognitive notion. However, it has been discussed that affections are an essential part of the metal model people follow to form their risk perceptions and to assess how dreadful an event could be. Loewenstein et al. (2001) introduced the term "risk as a feeling", in which the role of worry as an influencer in risk perception was studied. Under this concept, it is explained that people may perform subjective assessments of risk probabilities, based on their expected emotions or the level of fear a risk could provoke in them, in case negative consequences occur. This subjective assessment has been categorized as "expected future experiences" (Rundmo and Nordfjærn, 2017).

2.2.2 Cultural theory of risk

This theory was developed in the 1980s primarily by Mary Douglas and Aaron Wildavsky, in reaction to the common technical, rational and psychological understanding of risk perception (Douglas and Wildavsky, 1983; Slovic, 1987; Starr, 1969; Tansey and O'riordan, 1999).

The cultural theory of risk (CT) originated from contributions of various disciplines, such as anthropology, philosophy, sociology, social history, cultural geography and science and technology (Lupton, 1999). According to the CT, risk perception draws from societal preferences, recognizing a phenomenon as a risk or not subject to one's values and ideal social organization (McEvoy et al., 2017).

The CT of risk explains that people decide to express anxiety towards something in particular and to a certain level, inclined to endorse the manner they conduct their lives (Wildavsky and Dake, 1990). Under this theory, the term risk is understood as a social construct, in which members of a society are exposed to similar threats, but judge them differently due to cultural backgrounds associated to their lifestyles and worldviews (Douglas, 1992). Under this theory, risk perception derives as a "culturally standardized response" to risks and in accordance with socially shared ideologies (Douglas, 1992).

According to Douglas (1992), acceptable risks cannot be defined in statistical terms since every society sets the basis for what is a risk and to which degree would be judicious to take control measures. In facilitating the understanding of this concept, four main types of attitudes towards risks have been introduced under the CT, differentiated on the kind of lifestyles people have and their understanding on how societies should function in reference to risks.

The rationalities on these worldviews have been organized in a grid/group arrangement. People`s rationalities on their risk perception are ordered within four categories, as shown in Figure 7. Grid refers to people`s beliefs that their lives and social exchanges are strictly regulated, predetermined or restrained.

A group denomination makes reference to the degree in which a person feels part of a community and that his actions are influenced by those social organizations the individual belongs to (Krohn and Krücken, 1993; Kropp, 2002; McEvoy et al., 2017; Oltedal et al., 2004; Rayner, 1992). Hoogstra-Klein et al. (2012) applied the CT theory to explain people's perception of environmental risks and their involvement in natural resources management.

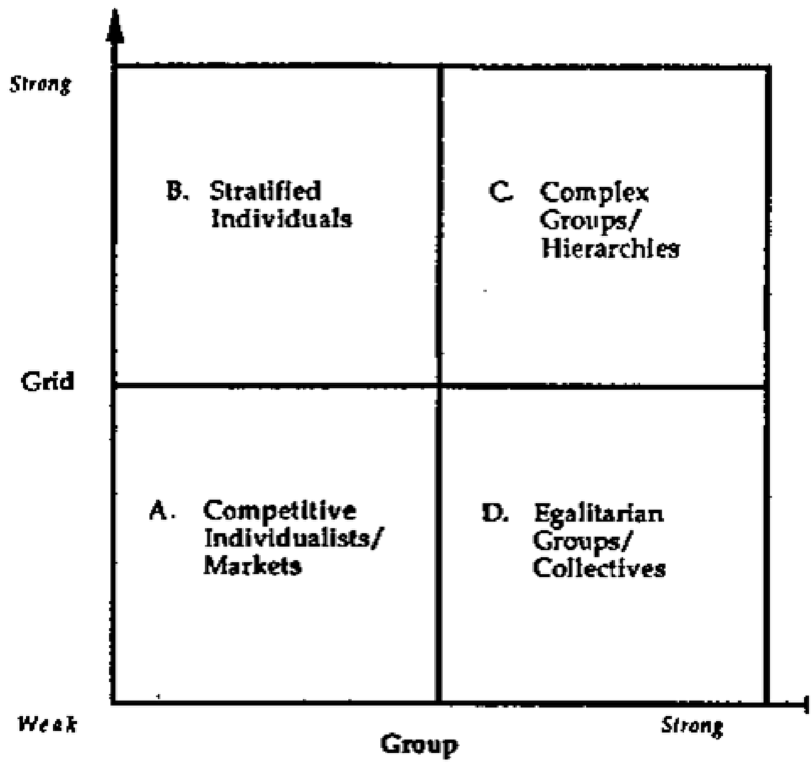


Figure 7. Grid-group typology of the cultural theory of risk.
Source: Rayner (1992).

The CT refers to them as A) Individualists (weak group; weak grid); B) Fatalists (weak group, strong grid); C) Hierarchists (strong group; strong grid); and D) Egalitarians (strong group; weak grid) (Hoogstra-Klein et al., 2012; McEvoy et al., 2017; Oltedal et al., 2004; Schwarz and Thompson, 1990).

Rayner (1992) compiled a list of attributes that characterize individuals within the grid/group notion of the CT, see Figure 8. Among the distinctive parameters he considered are their inclinations to social relationships, their sense of duty and level of specialization. People's characterization is done in reference to a low/high disposition to the parameters described, which is equivalent to the weak/strong distinction.

	Group	
	Low	**High**
Networks	Radical	Interconnected
Interactions	Rare	Frequent
Boundaries	Open	Closed
Shared activities	Few	Many
	Grid	
	Low	**High**
Accountability	Horizontal	Vertical
Specialization	Little	Great
Allocation of roles	Achievement	Ascription
Resource allocation	Egalitarian	Hierarchical

Figure 8. Characteristics of the grid-group attitudes.

Source: Rayner (1992).

Individualists

Based on the CT, people with an individualist attitude oppose things that can limit their autonomy; they are very independent (weak group), support the liberalization of markets and believe in financial freedom (weak grid) (Oltedal et al., 2004; Schwarz and Thompson, 1990). They believe that nature can restore itself after a disturbance. Thus, certain externalities are tolerable (Oltedal et al., 2004). Individualists have a firm view that nature can deal with the negative impacts of economic growth (Schwarz and Thompson, 1990). Under this rationality, individualists are less concerned about potential adverse effects if there are benefits they can enjoy linked with the risk issue. Individualists seek opportunities and accept risks provided that their freedom is not impaired (Oltedal et al., 2004).

Fatalists

These stakeholders remain distanced from social interactions (weak group) and would prefer not to be informed and concerned about risks since they believe damages are inevitable and they cannot influence the consequences. Besides, they feel under the control of people they do not feel associated with (strong grid) (Hoogstra-Klein et al., 2012; Oltedal et al., 2004).

In their understanding, nature operates parallel to human actions and thus, we have to deal with whatever phenomenon may happen (Hoogstra-Klein et al., 2012; Oltedal et al., 2004). Fatalists tend to not engage in political actions and prefer to deal with the consequences that derive from decision-making done by others (McEvoy et al., 2017).

Hierarchists

Individuals with a hierarchist risk rationality trust above all on the institutions and regulations to handle risks (strong grid). They rely on these orders and organizations as a means to keep the wellbeing in a society (Oltedal et al., 2004). Hierarchists seek highly structured systems and modes of work and they prefer a clear definition of rules and roles, which leads to societal specialization. Social relationships and responsibilities are characteristically crucial for hierarchists (strong group) (McEvoy et al., 2017). Their concerns relate to societal unrest, transgressions and manifestations since they challenge the "order" they embrace. These stakeholders entrust experts and representatives from public command to assess and manage risks and believe that nature is robust and can restore by itself from undesirable impacts, as long as regulations (e.g., limit values) are respected (McEvoy et al., 2017; Oltedal et al., 2004; Schwarz and Thompson, 1990).

Egalitarians

They oppose technologies or changes that may provoke inequality among people (Oltedal et al., 2004). Initially, this group was referred to as sectarians by Douglas, due to their similarity with [religious] "indoctrination" towards environmentalism and collectivism (Douglas, 1992). In contrast to hierarchists, these stakeholders exhibit great distrust to experts and regulatory organizations since they believe that they mishandle their power (weak grid) (Oltedal et al., 2004). Different to entrepreneurs or individualists, egalitarians have the conviction that nature is vulnerable due to the impact of human activities and thus, needs to be handled with care (Oltedal et al., 2004). Egalitarians advocate for the precautionary principle (cf. 2.5), aiming to avoid inequality derived from technological and environmental risks (McEvoy et al., 2017).

Egalitarians resist externally imposed control and disagree with hierarchical social roles definition since it challenges the ideas of fair social opportunities and equal application of rules. Different from individualists, egalitarians put a strong emphasis on collaboration and common benefits (strong group) (McEvoy et al., 2017).

In some occasions, one can find in the literature a fifth cultural classification of people's rationalities towards risks, namely, the hermit or autonomist. Under this categorization, people choose a complete rejection of social life. This fifth worldview is, however, regularly undecided to be considered as part of the CT of risk (Mamadouh, 1999).

Besides Douglas and Wildavsky, other authors approached the sociocultural dimension of risk perception, such as Ulrich Beck and Anthony Giddens with their concepts on the "Risk Society" (Adam et al., 2000; Beck et al., 2007; Engelhardt and Kajetzke, 2010; Japp, 1996). Another group is the "Governmentalists", based on the works of Michel Foucault (Lupton, 1999). In this investigation, we focus on the contributions of Mary Douglas and the risk perception rationalities.

2.2.3 Social amplification risk framework

This theory assumes that the social and financial consequences of an event are related to not only its tangible direct effects, but also, with the interplay of emotional, ideological and the sociocultural arrangement of society (Jaeger et al., 2001). The social amplification risk framework (SARF) was introduced by Kasperson et al. in 1988, as an alternative understanding to people's risk perception, considering aspects that were not explained under the psychometric and the cultural theory of risk (Jaeger et al., 2001) with a focus on the role of communicative environments of sense-making.

The SARF states that risk information is disseminated through different channels (especially the media), loaded with various sociocultural signals, becoming intensified or weakened on its transfer process, depending on the way the transmitters and stations react to the content of the risk message. In this theory, the mass media and social networks are the main drivers for conveying risk information (Mase et al., 2015). Figure 9 shows a representation of the different stages in which risk information undergo and linked impacts, as information is amplified or attenuated in society.

In association with other individuals, people intensify or weaken their views on risks and subsequently, their response to them. A change in their risk perception causes indirect consequences, exceeding the scope of direct impacts on people's health and the environment. Some of these outcomes are, for example, debts, harmed reputation and fines (Jaeger et al., 2001).

Understanding the implications of the SARF in risk management is crucial since they may incite the rejection of preventative measures when risks are lessened, or claim rigid control over risks from organizations and relevant societal actors when people aggravate risk issues (Jaeger et al., 2001).

Kasperson et al. (1988) developed the SARF and employed concepts of communication theory to explain how information on a risk event is adjusted along the way through different transmitters. Receptors may modify a message, incorporating or removing elements that characterize a risk issue. At each stage, the message transmitted contains value-related and meaning, depending on the stations it passes and is accompanied by signals to which people react (Jaeger et al., 2001; Kasperson et al., 1988).

Societal actors understand risk signals in different ways but under the influence of social groups, focusing on specific aspects of risk and extrapolating on potential consequences of an event. In this regard, social amplification affects the way individuals discern on risks, organize information on them and judge their relevance, in the basis of the interpretation of indicators accompanied with the risk message. This mechanism becomes then an influence on people's attitudes towards risks, determining their heuristics approach when dealing with risks in their daily lives (Jaeger et al., 2001).

Risk amplification means heightening and lessening features of risks either within organizations, social groups or from individuals. Based on their judgment, ideologies or political interests, social actors influence the interpretation of a risk message, which they then transfer to other members of the society (Renn, 1991). In this regard, risk perception evolves from a social construct and a partial feature of a risk phenomenon (Rosa, 1998).

Once information of risks is decoded, i.e., people's assessment of a message, in reference to their knowledge, affection and cultural inclinations, information on risks is passed on to other individuals or station of amplification (Kasperson et al., 1988; Renn, 2011, 1991). Some of the societal stations include news, organizations, public institutions and experts. Among the changes that may occur in the message are interpretations, selection of information, the addition of social value and promotion of distinct behavior and/or attitude. The results are among others, the generation of a risk perception in certain groups or the society at large, particular negative consequences in economic sectors or industries, social distress and movements (Kasperson et al., 1988; Renn et al., 1992).

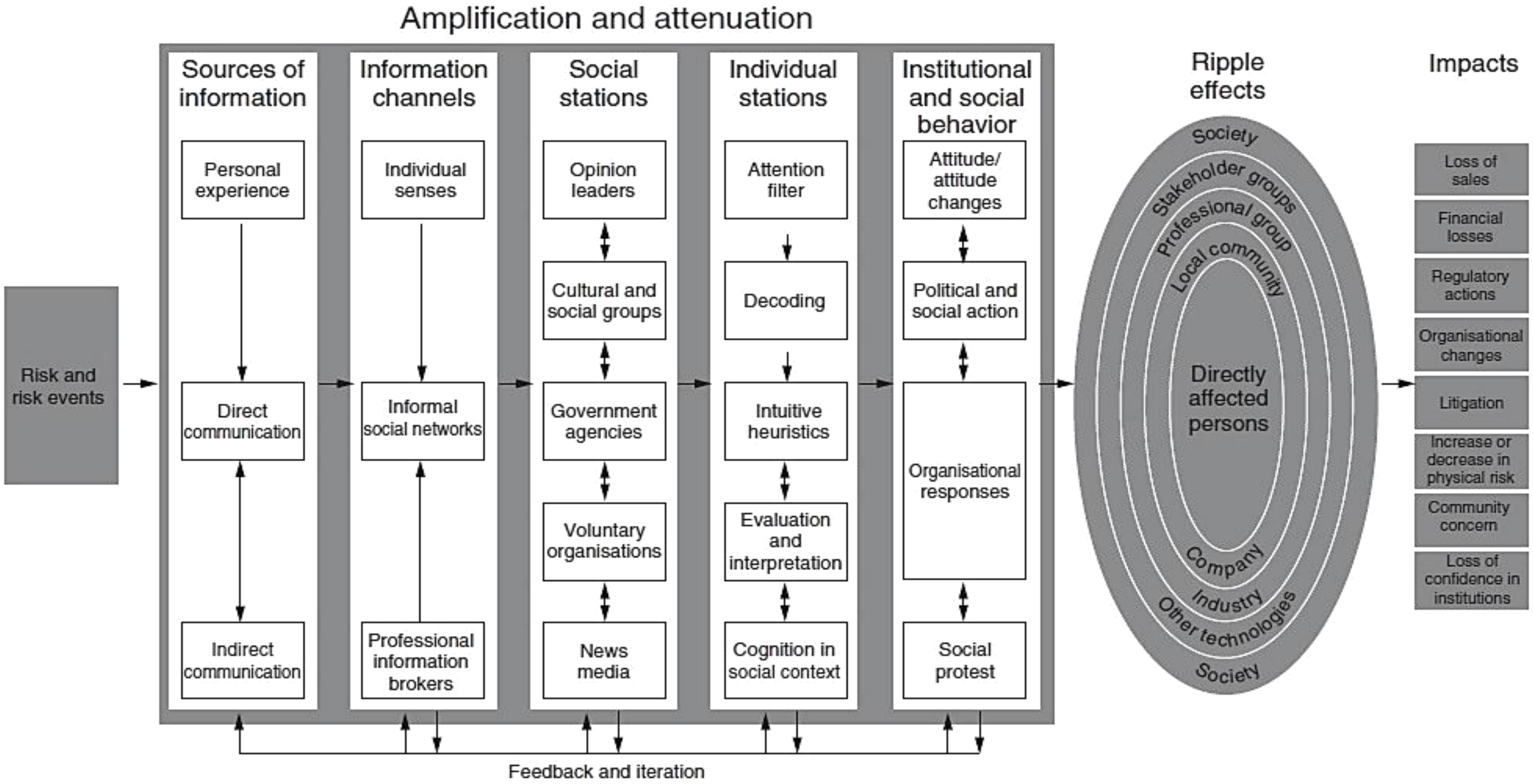


Figure 9. Representation of the Social Amplification Risk Framework.

Source: Pidgeon et al. (2003).

Impacts of the SARF go beyond the social transformation of a risk message. Individuals transform not only their view on a particular risk event or technology, which generates indirect effects, such as persistent rejection of a technology, social division and distrust in society. Moreover, these attitudinal changes cause losses in the economy as people change their behavior towards a risk source, there are associated sociopolitical demands and possible revolts, challenging the social order and technological acceptance can be increased or reduced as a results of a risk communication and social interpretation process (Jaeger et al., 2001). In the following sub-section, the concept of technology stigmatization is introduced, as a possible negative consequence of a risk amplification process.

The SARF and Technological stigmatization

When a risk topic receives high attention from the media and social organizations, the public starts to worry, causing substantial indirect consequences from what was an initial event and in reference to what has been termed as a "socially amplified" threat (Garrick, 1998; Kasperson et al., 1988). Information on a dangerous phenomenon is socially processed as described in the SARF theory, in which signals are associated with the risk at matter. A crucial feature of those socially heightened risks is their prospect of stigmatizing spaces, technologies and products, risking to make them entirely rejected, due to a prevailing unfavorable risk perception in society (Flynn et al., 2006; Flynn et al., 2001; Gregory et al., 1996).

Stigmatization occurs when a feature of a product or technology, an accident or a risky event is being depicted in the public opinion loaded with negative headlines. The result of this process is an enduring and far-reaching unfavorable effect beyond the direct consequences of the initial events (Kasperson et al., 2001).

On this point, stigma has been defined as "a mark placed on a person, place, technology, or product, associated with a particular attribute that identifies it as different and deviant, flawed, or undesirable" (Kasperson et al., 2001). Stigmatization is then a mechanism of assigning a characteristic to an individual, location, technology or commodity, in order to depreciate it and form an argument for the reasons of its inadequacy (Goffman, 1963). In the process of risk amplification stigma can be generated in relation to a risk issue, as depicted in Figure 10.

The stigmatization mechanism goes through three phases (Kasperson et al., 2001):

i) Characteristics of the risk phenomenon receive intense media attention, which causes the formation of judgments on the issue and the ideation of a threat on the communicated matter, as described in the SARF theory;
ii) The object, technology, individual and/or location associated with the threat is publicly distinguished, by assigning it a label or a “mark” and classifying it as particularly risky and thus, unwanted;
iii) People change their conduct toward the stigmatized issue due to the negative perception built causing various secondary effects. Also, those possessing the marked trait change their identity in the process of stigmatization.

The prominence of a marking or demeaning feature associated with an object, site or technology in the mass media is a central aspect in the process of stigmatization. Broadcasting about the risk issue emphasizes the social intensification or lessening of a stigma associated with it. The manner the risk is outlined and portrayed play also a vital role in this process. Besides, the reach of reporting, the kind of information selected to be presented and the manner the risk is phrased directly influences the process of technological stigmatization (Kasperson et al., 2001).

Besides, the prevailing public perception affects the process of stigmatization. When a risk is viewed as imposed and highly dangerous, people tend to exhibit strong fears and rejection. In addition, if there is a high level of trust in risk management institutions, risks will experiment little social amplification, however, the contrary is also true. Thus, risk communication strategies need to consider strengthening the level of trust in the prevailing social context of a contested technology (Kasperson et al., 2001).

The stigmatization or marking of a location, product or technology leads to a change in its character since it is then newly associated with distinct characteristics discrediting its nature. This transformation in identity is suffered not only to the location, product or technology but also reaches to all individuals associated with it, i.e., an inhabitant, stakeholders in an economic field or leaders dealing with the risk matter. The outcomes of the stigmatization imply significant losses that go beyond a single sector, location, technology or social group (Kasperson et al., 2001).

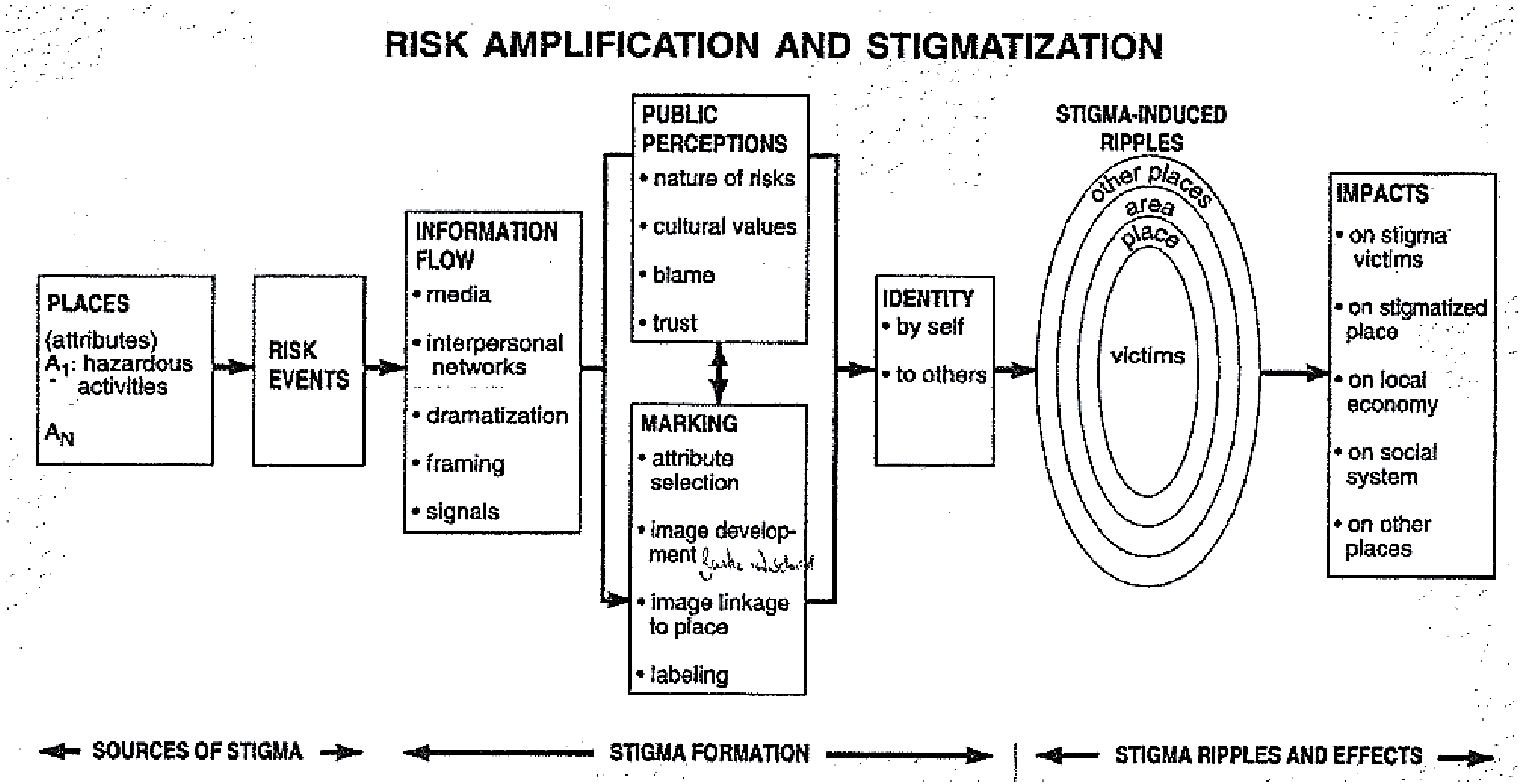


Figure 10. Relationship between the SARF and technology stigmatization.

Source: Kasperson et al. (2001).

2.3 Laypeople vs. expert risk assessment

The risk perception of social actors, either non-specialists or experts, influences decision-making and may cause significant effects beyond the direct physical influence of a risk matter. Their response to risks can be exhibited either as a simplification or as an overestimation of risks. Stakeholders' risk perception plays a crucial role in the identification and legitimation of what is considered threatening in a societal context and in the determination of management approaches to tackle those dangers.

Various authors have documented alleged differences in how laypeople and experts, e.g., from a particular industry perceive risks (Krewski et al., 2012; Savadori et al., 2004; Sjöberg, 1998); and some factors have also been identified to be determinant in the way these members of the society assess and handle risks (Bostrom, 1997; Skjong and Wentworth, 2001).

In diverse sources, laypeople's risk perception has depicted as illogical, seeing risks where there is none, while discarding important ones when they are assured by experts (Bostrom, 1997). This attitude has been critically termed as the "irrational individual" (Plough and Krimsky, 1987). After years of work in social sciences, it has been asserted that the mechanism of identifying risks involves not only the assessment of the vulnerability towards risks and the possible outcomes, which is the conventional risk interpretation; it also includes a value judgment or discernment towards the threat, ultimately represented in a cost-benefit estimation, view from a personal, collective or sector-related point of view (Granger Morgan, 1993).

This risk consideration is done in reference to what is seen as valuable and is subject to who is involved in the characterization of risk. In other words, people's risk appraisal goes beyond the technical interpretation of "probability and severity"; their (subjective) mental models to assess risks also include values, ideologies and cultural factors.

When it comes to risk management, various measures come into play, to balance the cost-benefit relationship in risk assessment, among them is to seek to modify the way individuals perform particular work, in order to reduce the perils of potentially undesired effects. Efforts targeted to change and assess people's risk perceptions are also part of risk management, as well as abatement and rewards measures (Granger Morgan, 1993).

Some interpret the influencing factors for risk perception in laypeople as a process of heuristics or "mental shortcuts" and inclinations (Bostrom, 1997), such as i) anchoring, centering in an initial estimate to make further assessments; ii) compression, referring to the deficient interpretation of probabilities in the presence of volatility, underrating or exaggerating the incidence of an event; and iii) availability, appraising risks on the effortlessness in which they are recalled, in which the media plays an important role (Fischhoff et al., 1993).

The anchoring effect may lead individuals to form wrong conclusions from sources of information since they may find particularities more believable than generalities (Linville et al., 1993). These heuristics and inclinations influence people on how they formulate risks, e.g., regarding advantage or disadvantages (cost-benefit assessment), generating in them an attitude of acceptance (optimism) or rejection (pessimism), for example, towards risks or technologies (Wang, 1996).

Other elements influencing risk perception among laypeople are their moral code and predilections, which are not considered in expects' interpretation of risk in a technical probability and severity risk assessment (Bostrom, 1997). In view of that, some authors have explained risk perception as a combination of a danger, from a conventional definition of risk) and a controversy factor, in reference to the multiple aspects described in the psychometric paradigm such as dread and acquaintanceship with risk, i.e., deliberate exposure, management over risks and awareness about them (Wandersman and Hallman, 1993).

Considering this evidence, it is widely agreed among researchers of risk perception, that people's risk perception is not the result of unreasonable worries or mere affections, but rather, it is subject to their sustained beliefs and ideologies, constructed from their mental models and which are built as a result of their social interactions (Renn, 1992). In this regard, there were arguments in the risk perception field suggesting that both experts and laypeople base their interpretations of what is a risk following different mental and social models (Wynne, 1992b).

On this matter, Irwin and Wynne (1996) proposed that research organizations need to recognize the social context in which their contributions are being made and the social constructions of knowledge or "contextual knowledge" derived from people's experiences as a source of expertise for their risk assessment. Instead of justifying on a "(knowledge) deficit" notion in people, he suggests recognizing the diversity of knowledge available, which complements the understanding of reality.

Plough and Krimsky (1987) explained that risk communication is an essential aspect to close the gap between expert and laypeople disagreement on risk perception. Risk managers need to consider both technical and cultural rationality to transmit information on risk strategically and thus, protect vulnerable groups in society from technological and environmental threats. On this aspect, Wynne (1992) argued that trust and credibility on experts and risk management institutions play a vital role in the reception of information by the society. Besides, people seem also to consider the kind of relationships that exist among the different groups and their perceptions regarding the interests they believe are followed by the risk agents and risk management institutions. Overall, a negative risk perception in people is lessened by strengthening trust in risk institutions.

Initially, it was agreed that expert judgment on risks was the standard to which the public risk perception had to be analyzed. It was alleged that expert discernment of risks was impartial and grounded on scientific risk appraisals, different to the subjective and affective nature of laypeople's risk perceptions (Slovic, 1997). Nevertheless, various evidence has been found to disagree with this notion (Merkelsen, 2011; Rowe and Wright, 2001; Sjöberg, 2002).

It has been postulated that experts do not assess risks differently than laypeople and thus, are not more unprejudiced than the common man. Various works have concluded that experts may be subject to social norms, influenced by the ideologies, values and preferences of their societal contexts (Rowe and Wright, 2001). Experts' views on risks may be thus partial, due to cultural dispositions, professional connections and even familiarity with a risk issue (Rowe and Wright, 2001; Sjöberg, 2002). It has also been debated that in cases of high uncertainty, expert opinion cannot be referred to as objective by decision-makers, who seek practical ways to handle lack of certainty. Furthermore, it needs to be acknowledged that people possess legitimate worries, independent of scientific evaluations (Merkelsen, 2011; Urquhart et al., 2017).

Another aspect is that expert risk assessment has been traditionally based on two main parameters: the likelihood of an event and the severity of the incident. The various interpretations of how to assess these two notions have led to opposing expert risk assessment results, e.g., if considering peaks, averages or weighted values in the appraisal. The focus and priorities in risk assessment have caused experts to obtain various results and understandings of risk consequences (Bostrom, 1997).

This situation leaves the public and decision-makers under uncertainty, lowering the level of trust posed in them since people interpret inconclusive results from experts as ineptitude (Sjöberg, 1999). In the risk society, expert knowledge is essential to obtain information and make conclusions on risks, however, it is not enough (Beck, 1992).

To understand both the nature of accidents and the legitimate acceptance and distribution of risks and benefits in society, risk identification and assessment has to incorporate the set of two: technical and social aspects of risks in a multi-disciplinary manner (Perrow, 1992; Renn, 1998b; Slovic, 1992; Starr and Whipple, 1980).

Besides the various ways a risk problem is framed, experts may also disagree when their value judgments on risks are considered in a risk appraisal. An example of this is in the case of experts selecting methods for data collection or processing, assumptions on their models or when deciding on a kind or source of data for which their statistical analyses are anchored. In this process, experts may take decisions on documented procedures or instead on more utilitarian terms, in which worldviews and preferences may interfere (Bostrom, 1997).

Other reasons that have been reported to explain why experts disagree among themselves are among others (Bostrom, 1997; Skjong and Wentworth, 2001): i) high reliability on available theories explaining a phenomenon; ii) lack of comprehensive understanding of complex structures and the interplay among multiple variables and their potential effects; and iii) omission to consider people’s errors when dealing with technologies and their potential reactions towards preventive measures,.

Experts not only disagree among themselves but also with the public. Some of the reasons proposed that explain this phenomenon are according to Sjöberg (1999):

i) Possible misinformation or lack of knowledge in some societal groups; however, care needs to be taken in this aspect since from a sociological point of view, risk is a normative term, which includes not only knowledge but also values, ideologies and preferences to identify what may be understood as risk;

ii) The existence of various interpretations of risk, i.e., how the risk term is framed;

iii) Self-selection of risks among professional groups developed in their careers;

iv) Professional interests or group pressures ("traditionalism") may influence experts to acquire a certain attitude towards risks;

v) The level of acquaintance with a technology may influence experts to believe they can regulate risks, thus, lessening their relevance or concern;

vi) Their public role may also determine expert judgment, e.g., as a protector of the public interest, they have a duty to warn people, while, promoters of a technology may see certain risks as less threatening;

vii) Political inclinations may influence people, but also experts;

viii) The influence of the media and the way different social groups react to it impacts their risk attitude (cf. SARF);

ix) Confidence in professional associations, governmental institutions and business clusters may lead experts to acquire a risk perception different to that of the public.

Experts knowledge does not substitute a probabilistic analysis in risk appraisal. However, it is of particular interest when limited information on a risk matter is available, notably, in emerging issues, technologies or events (Skjong and Wentworth, 2001). The assessment of expert risk perception can also be of relevance when the interest is to study expert's attitudes towards risks and its management and in the identification of possible sociocultural, professional or psychological factors inducing their risk judgments.

The analysis of the idiosyncratic disposition of experts towards a topic and the argument-stations they follow when deciding on a matter is part of the so-called "theory-generating" approach for studying expert knowledge (Bogner and Menz, 2009). The aim under the characterization of expert information is to understand how they perceive the world and the habits they develop, resultant from their practices and which are determinant of their roles in the maintenance and progress of society (Bogner and Menz, 2009).

2.4 Emerging technologies and stakeholder risk perception

Unwanted consequences may arise in the development of a technology, capable of injuring humans and polluting the environment. When dealing with mature innovations, the scope of damage could be effortlessly appraised. However, the reach of impacts in emerging technologies (and possible societal responses) cannot be straightforwardly determined since they are laden with incertitude, complexity and various understandings on its relevance and people's vulnerability (Köhler and Som, 2014).

The public acceptance becomes a critical risk in the growth of an evolving technology, which is strongly influenced by the way environmental, social and safety risks of the new machines are managed by its proponents (Köhler and Som, 2008). For example, in a study of the European Environment Agency (EEA) in 2001 was concluded that risks of emerging technologies between 1896-2000 were ignored and precautionary measures were not implemented.

This situation led to accidents associated with high economic and public losses. In light of these circumstances, they explain that people nowadays commonly exhibit suspicion and concern when assessing novel techniques (EEA, 2001). In this regard, Frewer (1999) suggests that prevailing moral codes in a societal context, trust of people in risk management institutions, agents responsible of risk control, risk communication organizations, together with the society's sense of engagement in the decision-making of risk management are essential aspects that can also explain the refusal of an innovation.

From the analysis of various technological cases, the EEA recommends the following aspects when dealing with risks of emerging technologies: i) not-knowing and incertitude should be recognized and tackled in decision-making; ii) sufficient research and observation should be provided in a continuing basis; iii) proposed risks and benefits should be studied together with alternatives and the arguments presented by different stakeholders; and iv) both laymen and expert knowledge should be taken into consideration along the risk assessment stage (EEA, 2001).

During the initial phases of development of a technology there is incertitude about potential adverse externalities of a technology, due to the lack of familiarity with the new concept and scarce technical comprehension on its scope of impacts. This aspect makes risk management more complicated and challenging to identify safer options (Köhler and Som, 2014).

“Paralysis by analysis” is the term that has been used when decision-makers choose to delay risk preventative approaches, as long as detailed information on the nature of a technological risk is not available (EEA, 2001).

The study of stakeholder risk perception is also of particular interest in the development of a technology, due to its preponderance in determining courses of action in the investigation, implementation and management of an emerging technique (Bernauer, 2003; Weisenfeld and Ott, 2011).

When identifying crucial elements for its governance, various stakeholders, e.g., scientists, civic groups, businesspeople and politicians, pose different risk judgments and are influenced by various factors determining their risk perception (cf. 2.2 and 2.3). The risk attitude of social actors will eventually pose relevant consequences on the deployment of a technology (Weisenfeld and Ott, 2011).

Moreover, in dealing with novel mechanisms, stakeholders from diverse interest groups, e.g., research, politics, business and the society in general, mostly impact the public opinion (and the later risk attitude in society), due to their participation in public discussions and by broadcasting information on risks (Scheufele and Lewenstein, 2005).

Various researchers have indicated that overall stakeholders ponder on risks and benefits of a technology, which shapes their risk perceptions (Schenk et al., 2008; van Dijk et al., 2015). Understanding the risk-benefit mental models of stakeholders is particularly relevant since it regulates the levels of technological acceptance in public (Gupta et al., 2012). These mental short-cuts are especially present when confronted with emerging techniques since people are less acquainted with the innovation and its operation. Besides, people tend to rely on prevailing expert knowledge to form an opinion about an emerging concept (van Dijk et al., 2015).

In a study among experts, van Dijk et al. (2015) found the following aspects influencing experts in their discernment process about a technology: a sense of need on the innovation, incertitude on its potential consequences, extent of people’s vulnerability in case of adverse outcomes and a possible societal refusal on the novel mechanism. However, van Dijk et al. (2015) concluded that due to the complexity accompanied in a risk-benefit appraisal, this aspect still needs further study.

On this matter, Hall et al. (2014) explained that various types of stakeholders pose different risk perceptions when dealing with new technologies due to different heuristics and subject to the kind of association with other social actors, e.g., building trust and the level of knowledge they possess about the technology. He based his arguments on the "Stakeholder Theory", in which people are classified as primary stakeholders, those with a stake in the innovation, e.g., businessmen, customers, developers of the technology; and secondary ones, those who are not directly linked with the development of an innovation, e.g., NGOs and independent groups (Freeman, 1984).

2.5 Precautionary principle

In situations when environmental problems or innovative technologies are characterized by high levels of uncertainty in relation to the magnitude, scope, kind or duration of an impact, the precautionary principle (PP) has been recommended as a preferred course of action (Pretty, 2007). The basis for its argumentation is that as long as scientific conclusions are unavailable about a particular environmental issue, any decision taken would be fruitless amidst lack of definite information on the matter (Pretty, 2007).

The term precaution has been interpreted in many different forms in various fields of work including science and legal literature (Pretty, 2007). Renn et al. (2004) suggested an inclusive definition of the notion of precaution (p. 3), defining it as *"a prudent and sound choice of response in the face of uncertainty".* In this light, they denoted uncertainty as a circumstance in which there are indications of potentially harmful or damaging events, however, accurate information on the risk is non-existent (Renn et al., 2004).

The PP emphasizes the need to consider three essential elements, to be able to effectively manage risks, namely: uncertainty, ambiguity and ignorance. One talks about uncertainty when it is possible to identify possible unfavorable outcomes, however, statistical analyses for determining their likelihood are not at hand (Klinke et al., 2007; Pretty, 2007; Stirling, 2007).

The PP suggests that a practical approach to deal with risk problems considering uncertainty is to recognize the prospect of various risk explanations (Klinke et al., 2007; Pretty, 2007; Stirling, 2007). The second aspect of risk problems is ambiguity, in which not the likelihood of their occurrence is the matter, but the possible consequences associated with it.

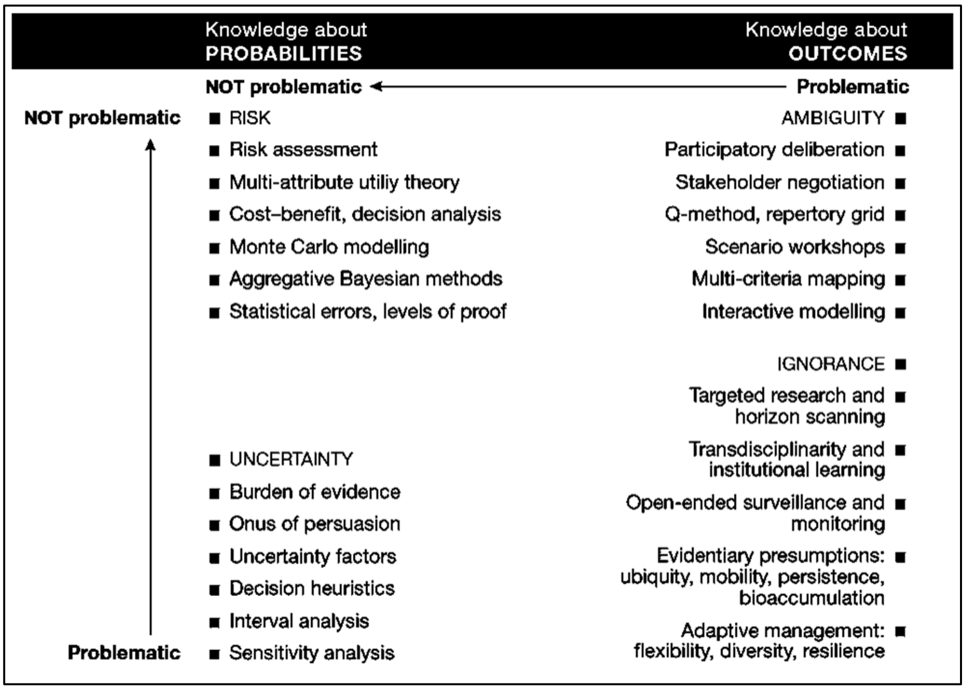


Figure 11. Procedural techniques when dealing with uncertainty, ambiguity and ignorance. Source: Stirling (2006).

Doubt arises from the different kind of effects that could occur, e.g., of environmental, societal, financial, or of safety-related nature. Therefore, ambiguity in risk matters carries in itself the problematic that further assessments do not necessarily represent more definite results (Klinke et al., 2007; Stirling, 2007). Lastly, ignorance complicates decision-making in risk management during situations in which neither likelihoods nor potential consequences can be specified. Issues associated with the risk problem are both controversial and inconclusive (Klinke et al., 2007; Stirling, 2007).

Stirling, a leading proponent of the PP, has emphasized that an important challenge of this notion is to deal with the constant demand of decision-makers, who regularly seek for practical and scientific-based answers to risk problems (Stirling, 2007). As a response, the focus should be given to the strength of the risk assessment procedure than to the precision of the answers requested (Stirling, 2007). Figure 11 shows some approaches that can be used in the assessment of risk problems in light of indecisiveness. In many occasions, agencies look for expert support on risk matters and follow rigorous methodological techniques and still, various understandings and results on risks appear. Stirling explains that the matter is on the different ways the risk problem is being constructed; for example, by defining outlines, specifying controversies or problems, allowing various methods and scientific fields, and comparing alternatives (Stirling, 2007).

In light of this situation, the PP serves as a guidance and a supplement to conventional risk assessment mechanisms, cf. Figure 12. This notion embraces both the normative interpretation of risk issues and recognizes the limitations that scientific knowledge may pose when dealing with a risk problem (Stirling, 2007). The concept of the PP is composed by various steps such as communication, screening and appraisal of the risk condition under various approaches, followed by evaluation and management (Klinke et al., 2007; Renn et al., 2004; Stirling, 2007).

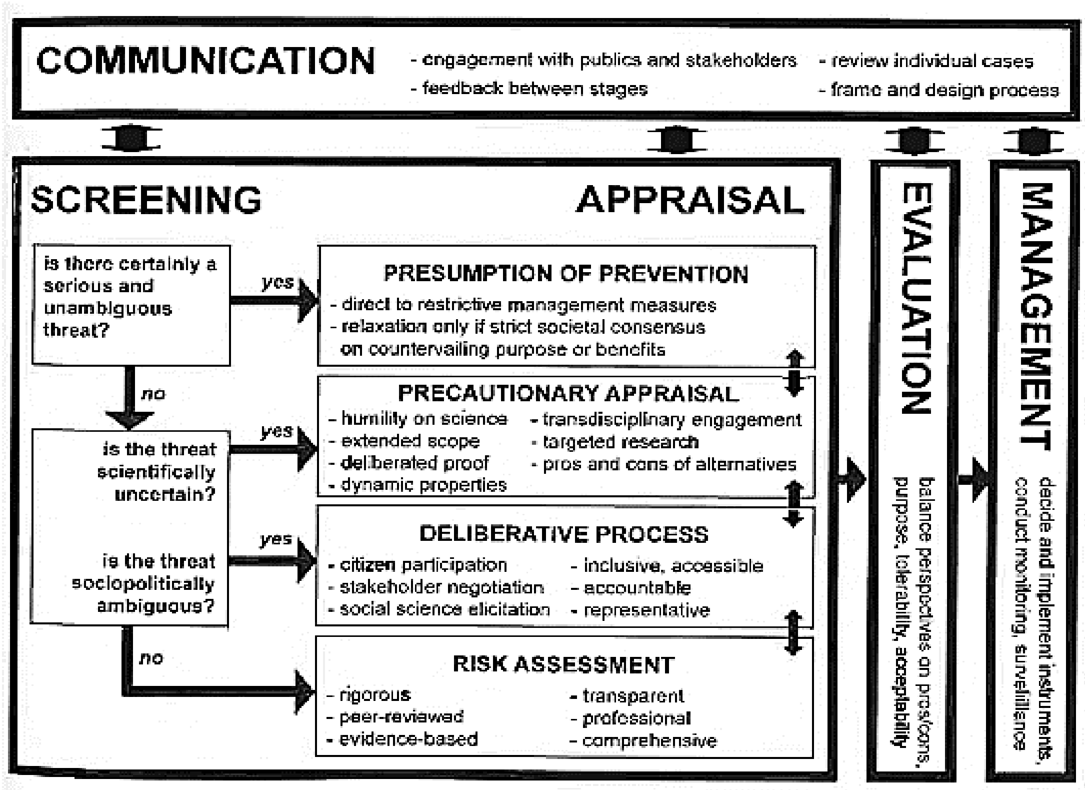


Figure 12. Association of risk management and the precautionary approach.

Source: Klinke et al. (2007).

2.6 Reflection on the theoretical background

The assessment of technology risk perception should always be considered in reference to the societal context of the study and by being aware of the societal role of the individuals participating in the risk appraisal, their possible interests and motives. Since multiple factors influence people to form an attitude towards risks, it is then necessary to acknowledge the role of psychological factors, social organization, affiliation, ideologies, affection and means of communication in the formation of a stakeholder risk perception towards a technology.

Interpreting what risk is, is always subject to what is considered valuable or worth protecting among people and social groups, which is ultimately a normative declaration. Decisions on when and how to protect individuals and the environment against risks can only be answered under a legitimate process. Besides, it is essential to take into consideration relevant stakeholders for the development and adoption of a technology.

Assessing how experts interpret certain technological risks can help to better understand which mental models may influence the stakeholder's decision-making in their accustomed management of a technology. Besides, it provides information on which sociocultural, affective and communicative factors may lead, for example, to accidents in a field.

When performing value-judgment, experts may also be influenced by similar aspects that affect laymen in their decision-making, such as their worldviews, familiarity with a technology and self-selection.

Uncertainty, complexity and ambiguity are characteristics that will permanently accompany decision-making of emerging technologies. However, strategic decisions need to be made on the basis of incomplete knowledge. In circumstances of new techniques, precautionary notions can serve as a guide to assess the nature of concerns among various stakeholders and to identify necessary actions amidst partial understanding of the extent of the danger of a technology or possible barriers in its diffusion.

Decisions on how to proceed with novel technologies and how to handle its risks and benefits, need to be done in contemplation of various interest groups. The concept of Risk Governance provides practical indications on the process of dealing with risks and the way of deliberating on stakeholder's engagement in risk assessment.

An essential aspect of this notion is its participatory, interdisciplinary and systemic nature. Once decision-makers obtain information on the technical and concern nature of a technology related risks and challenges, their agency to handle them will be successful only by the current institutional trust and transparency that people perceive in them, of special interest for communicating risks.

The theories described in this section serve as a framework to analyze the current perceptions of stakeholders in the German biogas sector on risks, benefits and challenges in association with PtG. Essential aspects from each of the theories described in this section will be used to explain the possible reasons and implications of the stakeholders' responses in the present study. The aim is to provide a comprehensive analysis combining all the notions portrayed here, with particular attention to the participants understanding on risk and what they believe is essential to handle for implementing PtG in biogas. Besides, their opinions on who is accountable for dealing with risks will be discussed.

Following on technology stigmatization, the author aims are characterizing elements that according to the interviewed stakeholders have been negatively reported in the biogas industry, which could remain after adopting this innovation. Besides, the scenario on possible image improvement of the biogas industry by incorporating PtG in biogas will also be considered, outlining essential aspects required to facilitate the risk management in the biogas sector and its innovations.

Drawing on the concept of risk governance, the author aims to describe crucial aspects for an efficient and effective risk management in the biogas industry and in association with PtG. The cultural theory of risk provides a guideline to characterize various attitudes of stakeholders in dealing with risks. In this study it is understood that a single individual could pose a mixture of cultural inclinations towards risks.

This investigation also describes factors that may have influenced the creation of certain mental models among the diverse interviewed interest groups and the argumentations they used to defend their positions. In addition, the author will draw on concepts of Sjöberg (1999) for understanding the roles experts acquired, in this study. This research will thus provide conclusions and recommendations on crucial elements for governing risks in the biogas industry and in consideration of PtG, as an innovation in the sector.

Chapter 3. Implementing Power-to-Gas in the biogas value chain

3.1 Biogas and the German energy transition

Nowadays, governments are challenged to provide more environmentally friendly energy sources. One of the main drivers for this change is the risk of climate change, urging the promotion of economic development based on a lower carbon footprint in contrast to conventional energy forms. Current political ideologies are anchored on the stimulation of higher returns on investment, energy sovereignty and less polluting technologies.

The German government promotes the transformation of its energy system under a political initiative named "Energiewende" or in English, energy transition. This transformation is part of a political strategy that initiated in 1990 under various controversies, however gaining broad public and political endorsement since 2011, after the nuclear catastrophe of Fukushima. With that strategy, it is aimed to reduce the carbon emissions in the country, while promoting energy efficiency through the expansion of the share of renewable energy sources (RES) by 40-45% in 2025 and 2035 by 55-60%.

The EEG has been a crucial driver for the progress of installation of and research on RES in Germany. As seen in Figure 13, the renewable sector contributed to approximately 218 TWh in 2017, equivalent to 33.3% of the gross electricity generated in the country. In 2017, this sector contributed with 12.9% in the heat supply and with 5.2% of fuel provisioned for transportation. On the same year, the Federal Environment Office (UBA) published that RES assisted in the abatement of 178.6 Mio. tCO_{2eq} (Umweltbundesamt and ZSW, 2018).

Concurrently, the German government has set the ambitious goal to diminish its GHG discharges in 40% to 2020 and 2050 by 80-95% opposite to emissions recorded in 1990 (Fischer et al., 2016).

With the purpose of supporting the expansion of RES, German political leaders enacted the Renewable Energy Sources Act (EEG) in 2000. This regulation guides the deployment of the renewable energy sector and has been adjusted several times, being in 2017 most recently amended (BMWi, 2018a). With this regulation, the German government has the goal to safeguard the provision of a more sustainable energy system and become less dependent from conventional energy sources, i.e., natural gas (BMWi, 2018a).

The biogas industry had a share of 5.4% of the energy demanded in Germany in 2017, corresponding to 32,500 GWh and a share of 1.4% of the heat consumed in the country, representing 17,184 GWh. In the form of biomethane, the biogas sector supplied 0.1% of the combustible employed in vehicles, equivalent to 380 GWh. The wind sector supplied 17.7% of the overall energy demanded and the solar sector had an input of 6.6% in the energy system (Umweltbundesamt and ZSW, 2018)

Within 18 years, the generation of renewable sources of energy, including biogas, has experienced a vast expansion in Germany. Records indicate that for the year 2016 more than 8000 biogas plants were running throughout the country, contrasting to the 1000 biogas facilities in year 2000 (FVB, 2016). Table 1 provides an overview on the number and kind of biogas plants operating in Germany according to their primary feedstock, i.e., fed with energy plants or a mixture with manure, biowaste and the ratio of plants upgrading to biomethane. The biogas sector has been associated with various benefits, but also to many liabilities. Biogas is a kind of bioenergy, which affords various opportunities, such as contributing in the reduction of GHG emissions vs. fossil fuels, facilitating the sovereignty in the renewable energy supply and a continued economic growth in the countryside (Florin and Bunting, 2009).

Table 1. Record of biogas plants installed in Germany in 2016.
Source: Daniel-Gromke et al. (2018).

Type of biogas production plants	**Number of biogas plants**
Agricultural biogas plants	Appr. 8,200
Thereof manure-based small-scale plants (≤75 kW) according to §27b EEG 2012/ §46 EEG 2014	560
Biowaste digestion plants (share of organic waste larger than 90%)	Appr. 135
Anaerobic digestion plants based on organic waste and manure/ energy crops (share of waste smaller than 90%)	200
Biogas upgrading plants (biomethane)	196
Biogas production plants, Total	**Approx. 8,700**

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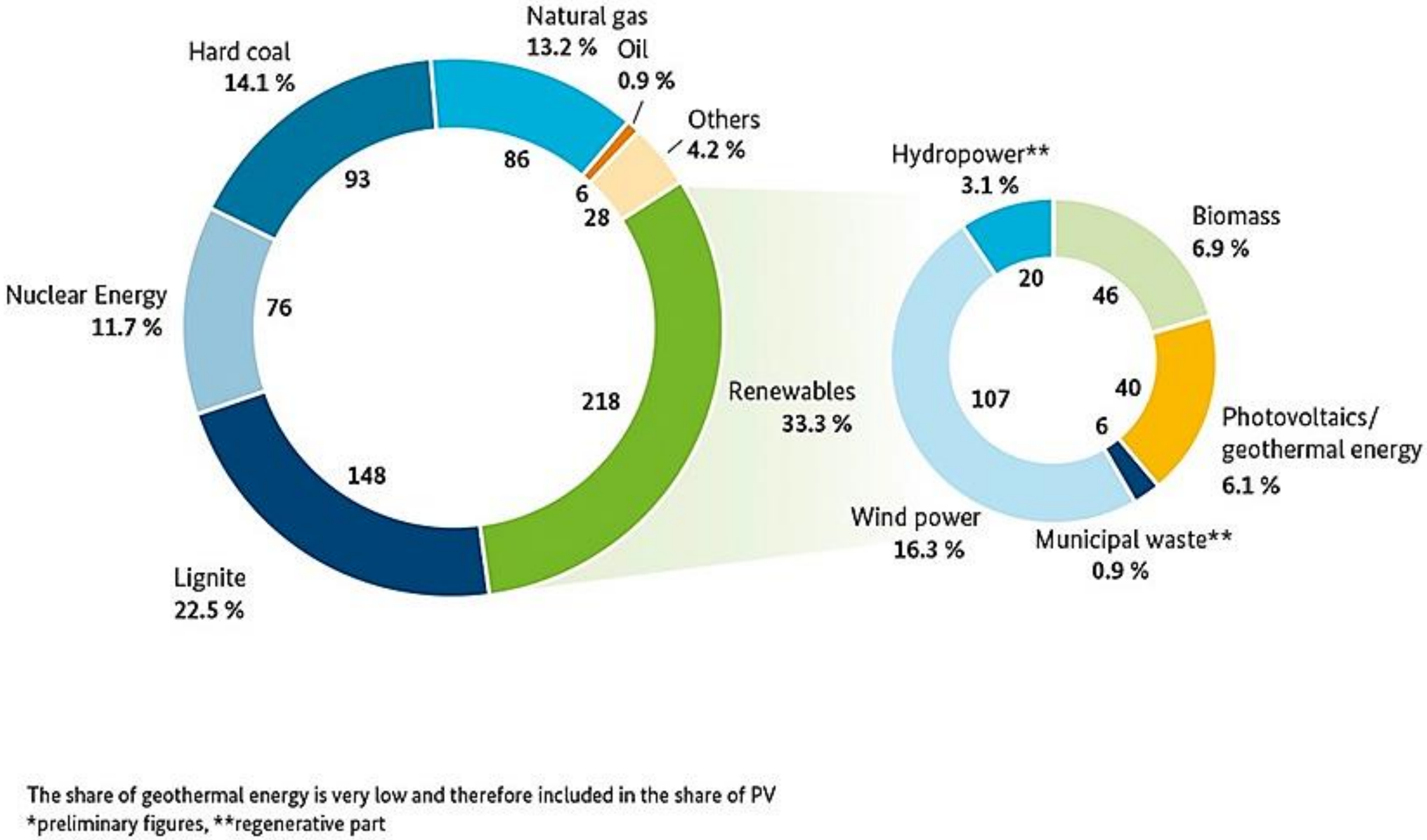


Figure 13. Global electricity generation per source type in Germany in 2017.

Source: BMWi (2018).

Despite the marked benefits of biogas, the expedited growth of this sector caused multiple impacts; among others, the intensification of maize cultivation, leading to significant environmental and economic effects, reflected in the augmentation of food and land leasing prices (Appel et al., 2016; Britz and Delzeit, 2013). Moreover, multiple accidents occurred associated with gas leakages and flare-ups (Casson Moreno et al., 2016; Trávníček et al., 2018), as well as fluid emissions into the environment, with microbiologically active substances (Keck et al., 2017; Kräft, 2015).

Furthermore, various studies showed that the development of the biogas production, associated with energy plants influenced the lending prices of agricultural land; which represented a fundamental shift in the farming sector, leading to replacements of production from food to biomass for energy generation. This change in agriculture caused significant distress to other fields, such as to the livestock farming and the food industry (Appel et al., 2016; Ostermeyer and Schönau, 2012).

In 2017, the EEG was modified, transforming and reducing the financial mechanism of the renewable energy system. The biogas business scheme of 20-year fixed contracts “Feed-In-Tariffs” was changed to a tendering model, subject to the energy demanded in the market. Besides, the new conditions of the EEG favor less expensive and versatile supply of renewable energy (da Costa Gomez, 2017). In light of this situation, the biogas sector is compelled to speedily adopt methods and techniques, like PtG, to adapt to new market requirements of environmentally friendly, affordable and flexible energy provision.

Besides the potential environmental impacts, various risks have been associated with the biogas value chain by handling flammable gases and by spreading health threatening substances. For example, the discharge of noxious and contaminating gases and the discharge of microorganisms that pose hazards to worker’s wellbeing, e.g., due to contact with germs and microbes. Other risks in biogas installations are related to energy cabling, posing a risk of high voltage impacts to worker or vulnerability due to magnetic fields and possible flames or outbursts (Bontempo et al., 2016). In reference to these incidents, Casson Moreno et al. (2016) reported 169 instances of accidents dealing with biogas installations in various countries, between 1995-2014. The investigators of that study observed that although modern and more efficient biogas installations were constructed, especially from 2005, the rate of accidents continues to increase in the biogas sector.

Figure 14 illustrates the trend of accidents linked to the biogas sector in Germany, showing a continuous performance since 2000, when the sector started its deployment within the country. This trend is similar to registers disclosed by the German Agricultural Occupational Health and Safety Agency (Maciejczyk, 2015). In the study of Casson Moreno et al. (2016), 96% of the mishaps happened within Europe and 76% of those were localized in Germany since the country is a leader of the biogas technology in the region.

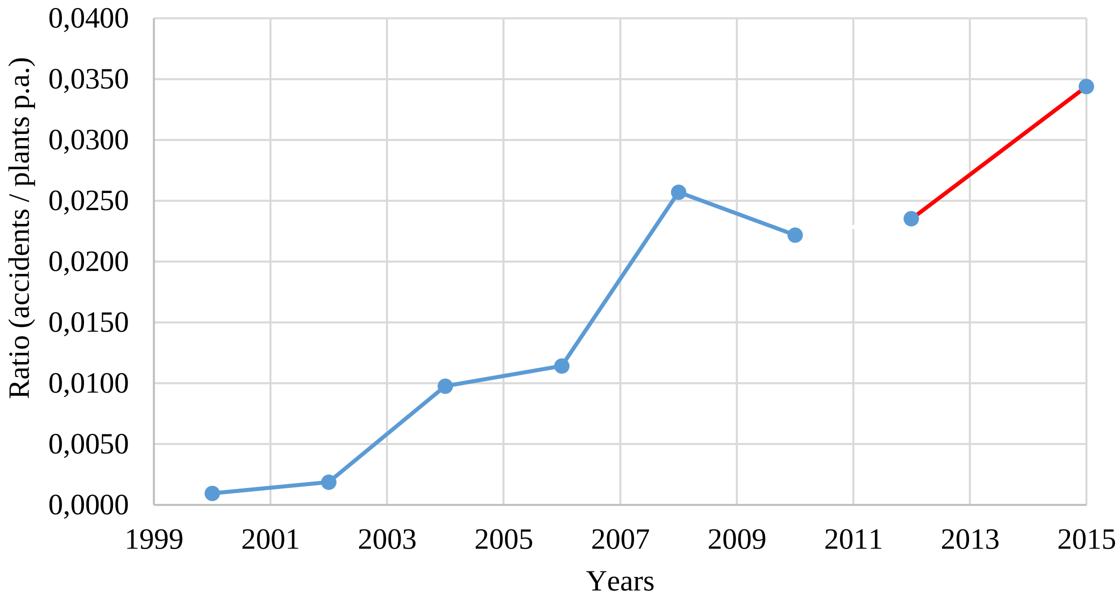


Figure 14. Ratio of accidents in the German biogas sector between 2000-2015. Source: Secondo Cividino et al. (2014) – blue line, Hauthal (2017) – red line and Fachverband Biogas e. V. (2017) – number of installed plants.

Results of a safety assessment performed in 300 biogas installations throughout Germany were published in 2015, showing conclusions of a group of specialists commissioned by the Umweltbundesamt or German Federal Environment Agency (Fendler, 2015). That report indicated that 73% of the evaluated biogas facilities in 2013 presented critical deficiencies regarding safety measures. In previous years, similar numbers were found, 71% of the plants were deficient in 2012 and 82% in 2011.

Fendler (2015) reported that the issues found in those installations were associated with low-risk awareness, inadequately built plants and untrained staff, together with non-conformity with safety procedures. Several of the identified risks in this report dealt with human behavior and attitude towards risks.

These deficiencies and misfortunes documented from the biogas sector, have occurred despite the availability of regulations directed to preventive measures, hazard protection and guidelines for best practices in the biomass processing sector.

Some of these regulations are the Technical Rule for Hazardous Substances (TRGS), existent since the ’70s, the fertilizer ordinance (Dünge-VO), the biomass ordinance and the soil protection law, Biomasse-VO and Umweltrecht - BBodSchG, § 17, since 2000, 1996 and 1998, respectively. Indications on caution areas due to potential explosions, the Explosionsschutzprodukte-Verordnung-11 (ProdSV), has been implemented since 1996 (Fendler, 2015).

Various authors have provided insights on the public opinion and acceptance issues concerning the German Energiewende and the biogas sector (Emmann et al., 2013; Fischer et al., 2016; Kabasci et al., 2012; Markard et al., 2016; Schumacher and Schultmann, 2017; Stiehler et al., 2013; Theuvsen et al., 2012). In 2016, the Agency for Renewable Energy (AEE) performed a representative survey on the consumer’s acceptance of renewable energies in Germany.

From that study was obtained that despite the general reception of RES in the population (93%), biogas was advocated for only 38% of the examined population. Although a higher reception is achieved if further biogas installations are done in already existing plants. Biogas was the least popular RES technology in that study, in contrast to solar and wind parks, which were supported by 73% and 52% of the sample group, respectively (Kimmich, 2016).

Stakeholders’ perception of risks associated with PtG and its adoption on the biogas sector is, nevertheless, yet a current knowledge gap in the field. The author found a recent study titled: “Livelihood Environment and its Security” (BWPLUS), which focused on a reception analysis of PtG among experts within the region of Baden-Württemberg (Köppel et al., 2017). The study contained in this thesis follows up on the BWPLUS investigation, in which the risk assessment of 27 participants from throughout Germany, experts in biogas and PtG, were interviewed on risks, challenges and uncertainties of implementing PtG in the biogas value chain. This investigation presents a comprehensive assessment, considering the opinion of various interest groups in the biogas sector, i.e., science, politics, industry and associations.

Based on this data, this investigation draws on the theories of risk perception and risk governance to analyze the perception of stakeholders in biogas towards risk management. The author derives recommendations to decision-makers and overall interest groups on ways to deal with risks, challenges and uncertainties of this technological concept in an efficient, participatory and legitimate manner.

It is relevant to analyze stakeholder risk perception on potential risks, challenges and uncertainties associated with implementing PtG in the biogas value chain, as a measure to identify areas of risk and controversies and to avoid any potentially negative impacts in the environment or on human health. Besides, it helps determining topics that could challenge the further development, diffusion and adoption of PtG as an innovation in the biogas sector, aspects that are of interest for investors, decision-makers and interest groups associated with the biogas industry in Germany.

PtG represents an attractive model for upgrading the biogas sector and transforming it to become more competitive in a flexible energy system. It becomes relevant to study present uncertainties and risks linked to this energy storage notion, together with the emerging use of biomethane as a carbon source in the chemical industry, which is of high interest in developing a bioeconomy strategy.

3.2 Power-to-Gas: an energy storage concept for the biogas value chain

Despite the environmental and safety risks confronted in the biogas sector, new technologies are being developed and adapted in its value chain; aiming at storage of surplus renewable electricity and a flexible power provision.

PtG is a novel technology that offers biogas installations the opportunity to generate biomethane in a versatile manner; at the same time, it assists them lessening carbon dioxide emissions, exhausts of the biogas conversion mechanism. In this process, biological methanation already takes place, thanks to archaea, specialized in the generation of biomethane. This conversion step, conventional in biogas plants, is well-matched with the concept of PtG since various criteria are met for the conversion of hydrogen and carbon dioxide into biomethane (Bailera et al., 2017; Meylan et al., 2016).

Figure 15 illustrates the process flow of the concept of PtG in connection with a methanation process, as available in the biogas production. Excess renewable energy is available from unsteady renewable sources, mainly wind and solar. The energy is not processed in combined heat and power (CHP) turbines; the power is then directed to an electrolysis tank, the first step of a PtG concept. There, H_2 is generated from partitioning a water molecule and having O_2 as exhaust (Götz et al., 2016; Meylan et al., 2016).

For this process to work, a carbon source is necessary. Among the various technical options, biogas offers a significant opportunity, since is relatively cheap and there is an infrastructure available in Germany. Through a methanation process, H_2 and CO_2 are combined to generate CH_4; thanks to the work of specialized archaea in biogas reactors. This biomethane could then be stored in the natural gas grid and later could be used for heat generation, for transportation (Götz et al., 2016; Meylan et al., 2016), or for an emerging use, as a platform substance in the chemical industry, an aspect presented in section 3.3. The implementation of PtG in the biogas sector offers the main benefit of stabilizing alternating renewable energy sources and making use of the existing gas pipeline network to store biomethane.

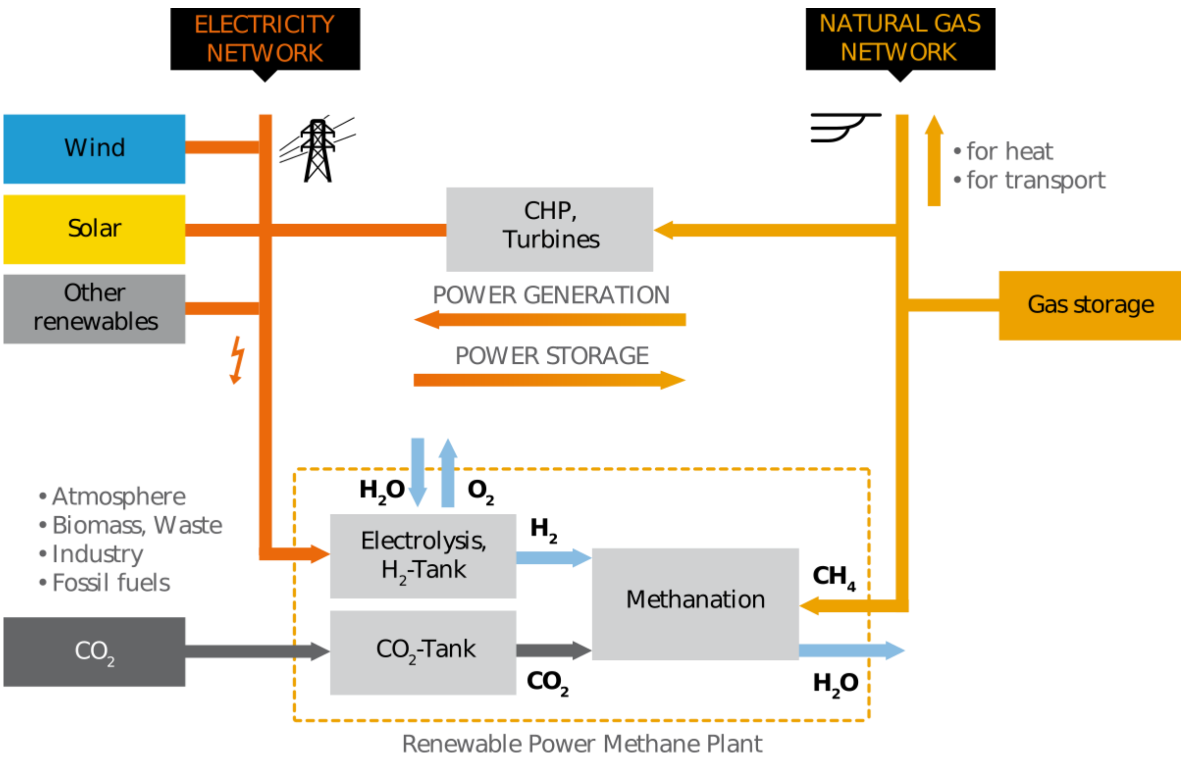


Figure 15. Sketch of a PtG concept connected to a methanation process.

Source: Klaus et al. (2010).

Anchored on the concept of the Energiewende, promoted with economic incentives by the German government, energy from wind and solar sources are expected to increase in the country in the years to come. A challenge with this concept is that these installations are subject to the state of the weather, causing variations in the energy supply (Lauer and Thrän, 2017). The biogas process could become an essential part in the stabilization of alternative renewable energy, in combination with the concept of PtG.

Various models have provided information on the scope of the expected energy deficit from renewable energies. For the year 2020, excess renewables could vary between 1.1 – 13 TWh (Stiller et al., 2010). Due to various assumptions, other models project greater deficits, ranging between 1.8 – 20 TWh by the year 2025 and 2040, respectively (Statista, 2018). An example of the unbalance in the energy system is provided by Klaus et al. (2010) as depicted in Figure 16. In the year 2009 was recorded a surplus of renewables in Germany up to 153.9 TWh, while the total energy deficit reached 52.8 TWh. Besides, cases of excess energy generation were distinguished to be more frequent than deficits. Lacking storage capacity makes it impossible for the renewable sector to supply the energy demands in the country.

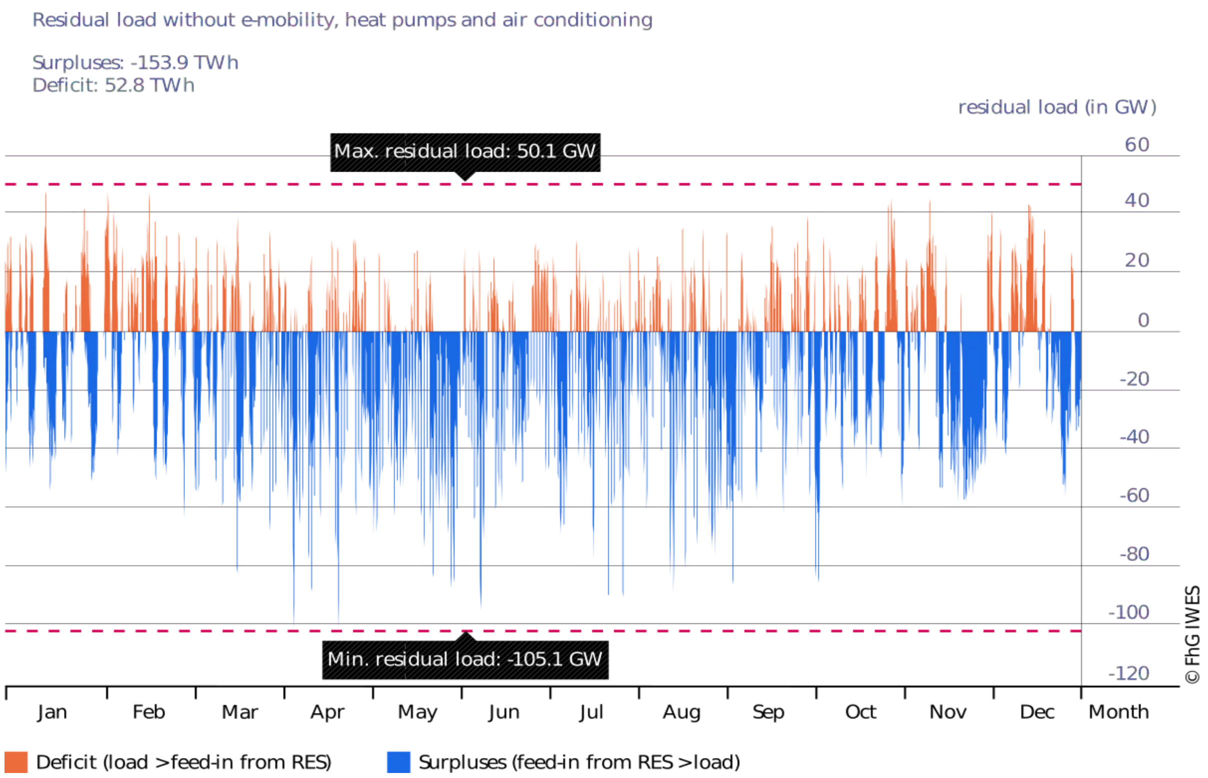


Figure 16. Fluctuating energy supply and demand in Germany in 2009

Source: Klaus et al. (2010).

While confronted with this condition, techniques aiming at the storage of excess renewable energy turn out to be essential to balance the energy grid in Germany. PtG associated with the biogas production scheme represents an opportunity to achieve the energy and climate goals of the German government.

Figure 17 shows the location of various PtG projects and their status throughout Germany as reported by the German Energy Agency (DENA) in 2017. Most of the installations are running (in Betrieb); while few are in the preparation (in Vorbereitung), planning (in Planung) or in the construction (in Bau) phase.

Figure 17. Distribution of PtG projects throughout Germany in 2017.
Source: DENA (2017).

3.3 Emerging use of biomethane as a carbon source

The adoption of biomethane as a substitute for natural gas, lessens the dependency on fossil-fuels and assists in the transformation towards a bio-based economy (Moghaddam et al., 2016). Once biogas is upgraded, biomethane can be transported and stored in the gas network, allowing its further use as a base chemical for the generation of various substances and materials of interest in the chemical industry (Weiland, 2010). The conversion of biomethane into various platform substances is done via a direct and an indirect conversion process, yielding e.g., formaldehyde and aromatics (Lunsford, 2000).

Since biomethane has similar characteristics to natural gas, it offers opportunities to generate syngas (a combination of carbon monoxide and hydrogen); from which platform chemicals can be derived from active chemical reactions. Methanol is a common substance generated from such catalysts. From methanol, various compounds can be obtained, such as ethylene, propylene and gasoline, which are primarily produced in the chemical manufacturing sector and are also crucial substances for the creation of many indispensable compounds in the chemical industry (Gill et al., 2011).

Methanol is composed by an alcohol, which can be employed as a fuel or could be mixed with gasoline to generate dimethyl ether (DME), which can be used in substitution of biodiesel or for direct fuel cells (Liu et al., 2007). DME could be employed as a base substance, among others, for manufacturing sprays, coolants and as a combustible for soldering (Semelsberger et al., 2006).

Also, microorganisms capable of metabolizing biomethane (*Methanotrophs*) could be adopted in a bioeconomy strategy. They can generate protein useful as auxiliary feeds, or for producing various substances, such as ectoine and sucrose, biopolymers and surface layers. Their plausibility in the market has been associated with the level of investment required, throughput, the productivity of conversion and the market price (Strong et al., 2016).

Chapter 4. Methods

4.1 Research design

To obtain the opinion of multiple stakeholders, experts in biogas and PtG, the author applied qualitative interviewing in this study, as the socio-empirical method for data collection. Semi-structured interviews were used to provide flexibility and obtain supplementary information in the process of gathering qualitative data. The analytical approach was performed inductively.

Figure 18 depicts the main phases that comprised the research strategy of this study, to obtain and analyze the unit of investigation. This approach is described in detail in the following sub-sections.

4.2 Semi-structured interviews

Interviewing is a method of social sciences, in which the researcher orally presents inquiries to a relevant source, in search of data to explain their conduct, understandings and emotions in relation to a particular topic (Crano et al., 2015). Although being work-intensive and demanding plenty of time, interviews assure obtaining explanations from participants instead of statistical correlations, which other methods cannot guarantee, e.g., surveys. Interviews are the ideal technique when the research matter requires collecting rhetorical contributions from a selected group of participants (Crano et al., 2015). In this research, qualitative interviewing was selected as the method of investigation since it facilitates obtaining judgments from the interviewees, about their perceptions on risks, benefits and challenges of implementing PtG in the biogas value chain.

Interviews can be executed in multiple formats, i.e., written, in person, online. The author used a face-to-face setup for this research, easing the participation of the interviewees, who did not have to travel to provide their insights. In addition, this arrangement allows the researcher to recognize possible misinterpretations on the way a question is phrased, hence, permitting the adaptation of the questionnaire to the purpose of the study. Moreover, the interviewer can explain in more detail any doubt the interviewees may have when confronted with the inquiries (Crano et al., 2015).

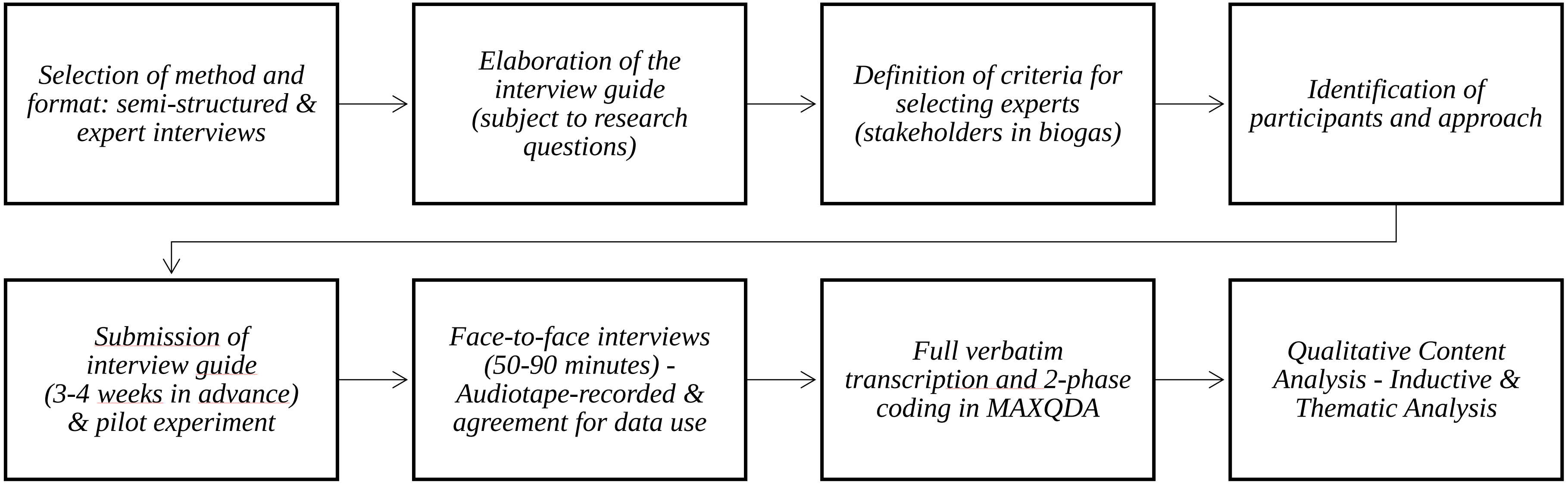


Figure 18. Procedure in this investigation for data collection and analysis.

When designing the research method, the analyst can decide among various configurations to outline the interview, either as unstructured, structured or semi-structured. The type of setup changes depending on the existence of assumptions by the researcher and of evidence on the matter under investigation (Crano et al., 2015). Despite constraining the research within particular topics, losing a broader perspective on the matter, this approach is valuable when the researcher has a demarcated theme, concentrating the investigation to that central concept (Crano et al., 2015), as it is the case of the present study, framed within perceptions on biogas and PtG.

Semi-structured interviews are recommended when the investigator possesses some background information on the research topic but does not want to dispose of the interview to strictly established questions. In this format, inquiries are then not asked uniformly to all participants or presented in the same sequence (Crano et al., 2015). These kinds of interviews are also called "structured-nonscheduled interviews", which means that there is a list of themes already pre-established by the researcher that should be considered in the interview; however, during the course of the consultation the investigator chooses the questions and the mode to pose them (Crano et al., 2015).

With semi-structured interviews, the researcher seeks for certain kind of evidence on the subject. However, there is no resolute itinerary on how to collect that data (Crano et al., 2015). As a pre-requisite, the researcher should be aware of indicators from the literature, justifying the questions formulated. Moreover, it is recommended the interviewer to be knowledgeable on the technical issue since it helps to guide participants to the essential topics of the research. Whereas answers vary from person to person, this technique is not ideal to demonstrate premises, but rather to serve as an exploratory approach (Crano et al., 2015).

4.3 Interview guide and pilot tests

An interview guide compiles the various questions or subjects the researcher aims to cover with the semi-structured interviews. The respondents, on their part, have all freedom to answer those questions in a broad sense (Bryman, 2012). Moreover, inquiries are posed randomly, not following a strict order. If the interviewee brings about relevant information for the research at hand, the researcher can emphasize on those topics and elaborate further questions ad libitum. Nonetheless, all queries designed in advance should be investigated, using similar expressions throughout the whole process of data collection (Bryman, 2012).

Following the empirical method of semi-structured interviews, a guideline was designed in advance in this study, having as reference the research questions (cf. 1.2). This interview guide (cf. Appendix) was distributed among the stakeholders 3-4 weeks before the interview. The guideline comprised a total of 15 open-ended questions, which were organized into three sections as indicated in Figure 19:

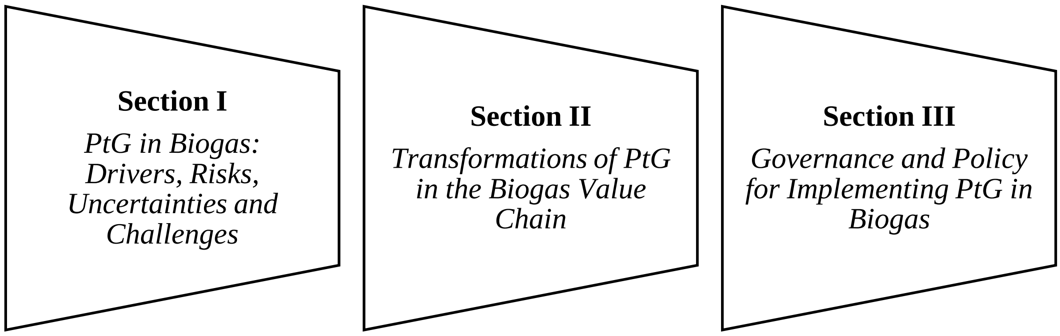


Figure 19. Content and structure of the interview guide.

The interview guide employed in this study encompassed the following topics:

Section I focused on the assessment of opportunities, risks and barriers associated with the adoption of PtG within the biogas sector. This section included multiple aspects, such as questions for judging benefits, competing technologies and potential risks embedded in the association of biogas with PtG. The risk perception assessment included the following domains: technology performance and economic aspects, potential direct or indirect environmental impact and lastly, societal and political challenges. The stakeholders were also asked to mention actors they expect should act to handle risks, challenges and uncertainties and to recommended management options for the issues they mentioned.

A definition of risk was not provided to the stakeholders and they were not asked to define the term. In contrast, their interpretations of risk were derived from their responses. It was of interest to determine what the stakeholders consider is a risk in their field and in association with PtG.

Section II concentrated on the implied transformations for the German biogas value chain hidden in the implementation of PtG in its production scheme. The analysis considered an appraisal of potential modifications in actors of the biogas sector, about their kind of cooperation and roles in the field.

Moreover, potential substrate mix as carbon source was also discussed with the participants. At last, conditions necessary for the development of a biorefinery concept were reflected in this section, considering biomethane as a bioeconomy product.

In section III included questions about the position of biogas in the German energy transition and in relation to the governmental climate protection strategy. The political perception of biogas was discussed together with the nature of support necessary for the continuation of the sector in association with PtG. Moreover, stakeholders were asked to assess the impact of the public opinion on the energy policy influencing the biogas sector and its innovations. The stakeholders were also requested to describe measures that they believe could ease a correct understanding and acceptance of PtG and biogas in the public.

In this study, the first three interviews were designed as pilot tests, which assisted to subsequently adjust the interview guide. The content of those interviews was integrated into the dataset analyzed in this investigation.

Pilot experiments provide multiple benefits, such as i) assisting in the identification of confusing questions to either adjust or remove them from the study; ii) assessing the overall time needed to complete the interview, thus deciding if it is feasible or not; iii) establishing the relevance of specific questions in the frame and scope of the study and identifying if they lead to appropriate answers; iv) realizing if all necessary questions have been considered; and v) assisting the researcher performing and refining interviewing skills (Dikko, 2016).

4.4 Sampling approach and criteria for stakeholders' selection

The technique of purposive sampling was used to select the interviewees of this study. Overall, the goal of purposive sampling is to consult participants in a deliberate way, suitable to the research questions at hand (Bryman, 2012). With purposive sampling, the selection of participants is made in line with the aims of the investigation, fulfilling various criteria determined by the researcher (Bryman, 2012). Besides, choosing individuals who are well informed on and familiar with the matter under investigation, they should demonstrate readiness to contribute in the study, providing well-thought viewpoints (Bernard, 2011).

The investigation at hand focuses on an innovation pertinent to the biogas industry, thus, the interviewees were selected in accordance with their relationship to this sector and their expertise in the biogas value chain.

The author approached participants who fulfilled specific conditions, namely, that they could demonstrate sound knowledge in biogas, its by-products and/or its innovation through PtG. Bryman (2012) indicates that when the characteristics of contributors in a study are predetermined, one calls that approach participants' sampling. Moreover, context sampling was followed in this study, constraining the research within Germany as a geographical framework.

Besides their expertise, the author aimed at reaching participants from various sectors with influence in the German biogas industry, choosing individuals that could provide insights on the research questions from different interests or standpoints. The sectors considered in this study were sciences, industry, politics (incl. related state institutions) and associations (incl. professional groups). Further details on the criteria used for choosing the participants of this study and for the characterization of their expertise were the following:

- A person who has been working with the biogas technology for multiple years in the industry; or
- Someone who has published or is currently researching on biogas, biomethane or the technology of BM/PtG; or
- A participant who works for an association or a political organization during various years, dealing with traditional and current topics about biogas and its derived products.

Specifics of the stakeholders considered and features of the interviews are presented anonymously in section 4.5. The contributors were identified by searching for recent publications in journal catalogs (e.g., Scopus, Science Direct and Google Scholar); inspecting databases of regional research projects, e.g., Agency of Renewable Resources (FNR), the BioEconomy Cluster and the funding program Energetische Biomassenutzung – Energetic use of biomass; searching for regional conferences, e.g., by examining publicly available list of speakers, conference proceedings and list of participants.

Besides the previous non-probability sampling technique, the author employed the snowball method to expand the list of potential contributors to the study. In this approach, initially selected participants are asked to recommend and even approach further stakeholders that fulfill the sampling criteria due to their knowledge or profile related to the matter under investigation (Bryman, 2012; Crano et al., 2015).

Contributors working in renowned institutes, companies, associations and political organizations related to the biogas sector in Germany were approached directly. Referrals could approach individuals whom they may know in person or that are part of their network. All participants were then invited via email, explaining them the aim of the study and asking for their contribution in the investigation.

The snowball technique facilitated reaching certain individuals, who otherwise might have been difficult to enlist; besides, it was possible to integrate well-known actors in the biogas sector, crucial for obtaining a pertinent judgment in the field. To avoid segmenting the contributions, inviting only suggested participants who share certain qualities, this technique was only used as a complement of the purposive sampling, which was described before. This way, the scope and diversity of contributors were broadened. On this point, it is appropriate to remark that despite their conveniences, these sampling techniques cannot represent an entire community, but the group of consulted individuals (Bryman, 2012).

4.5 Identifying experts in this study

As described in the previous subsection, the main criterion for the selection of the participants was their expertise in the German biogas context. Besides, participants were chosen considering their affiliation, representing the interests of one of the sectors indicated in the previous section. The stakeholders were identified by their track record in the field, someone who could provide comprehensive insights on risks and challenges confronted by the implementation of PtG in the biogas value chain.

In academic studies, an expert is a proficient person in a specific area of knowledge, selected by a researcher as a source, according to particular questions under analysis (Meuser and Nagel, 2002). In a more elaborated form, an expert is someone who holds “institutionalized authority to construct reality” (Hitzler et al., 1994). Hence, expert knowledge can be distinguished by its prospect “to be influential in structuring the conditions of action for other actors [....] in a relevant way” (Bogner and Menz, 2002).

In this research, the author followed this conceptualization of expert together with the notion of stakeholders of the German biogas sector from different sectors of influence, as a means of “pluralistic” social knowledge creation (Gibbons et al., 1994).

The concept of stakeholder was understood as individuals or clusters that are subject to a field or business, affect its development or have some leadership or authority in its public view (Gerkensmeier and Ratter, 2018).

Despite existing criticism on the robustness of expert interviews as a research method due to the absence of normalization and reduced possibility of numerically estimating obtained contributions (Bogner and Menz, 2002), expert interviews proof to be a valuable technique of scientific investigation for: “i) [knowledge] exploration, ii) [knowledge] systematization and, iii) theory generation [in social sciences]” (Bogner and Menz, 2002).

Besides, expert interviews ensure to be speedy, smooth and reliable for collecting up-to-date data and providing the outcome of using direct application (Meuser and Nagel, 2002). As an exploratory method, expert interviews provide a guideline in emerging or complex subjects or as an auxiliary source of data (Bogner and Menz, 2009).

Expert interviews could also help to obtain information exclusively available among specialist groups, referring to their familiarity with the topic and customs in the field (Bogner and Menz, 2009). Finally, expert interviews assist researchers to generalize from observations, generating a theory. The investigator analyzes implicit ideologies, discernment and attitudes experts develop in their fields, which have social implications (Bogner and Menz, 2009).

These distinct aspects of expert interviews were particularly relevant for the study at hand, investigating implications of and requirements for adopting the emerging technology of PtG in biogas; and for assessing the expert opinions and attitudes in the management of risks, benefits and challenges associated with these technologies.

4.6 Characteristics of the interviewees

The expert interviews were performed until saturation was reached, meaning that for each additional interview performed in this research, no new information was found. A definite number of interviewees was set in advance, neither for the whole study nor per sector. The aim was to achieve data saturation.

Under this concept, the amount of interviews determining the sample size of a study is resolved once the researcher has obtained a conscientious understanding that the data collected is consistent and has been “exhausted” (Bryman, 2012).

In this investigation, the author applied the notion of data saturation by performing interviews until it was evident that no innovative or significant information appeared regarding the research questions and the provisional category tree, while further interviews were performed.

In total, 27 interviews were carried out during the field-work of this investigation, which comprised a period of 5 months. The author obtained:

- 9 participants from science (i.e., working in universities, independent research institutes or specialized think tanks);
- 7 contributors from industry (i.e., companies dedicated to the construction and maintenance of biogas plants, PtG installations or trading biomethane);
- 6 stakeholders from associations (i.e., representatives of and in contact with industrial or farm-based biogas producers, as well as expert groups in biogas) and lastly;
- 5 participants from politics (i.e., representatives of governmental institutions and a full-time politician).

Figure 20 shows a distribution of the different sectors represented by the stakeholders that participated in this study. The ratio of the sectors in reference to the total sample is indicated in percentage under the absolute value. These stakeholders worked in institutions distributed all over Germany as shown in Figure 21. Due mainly to limited time and financial resources, it was not possible to include farmers in the present study. Considered stakeholders were interviewed face-to-face, in their working spaces. Details about the participants and the interviews are shown in Tables 2 and 3 in an anonymized form.

The interviews had a duration of 50-90 minutes and were performed in German or in English, as the participants preferred. At the beginning of the consultations, the participants received an explanation about the scope and aims of the study and the procedure of the interview. Under their consent, each interview was audio-recorded and their affiliations were made public.

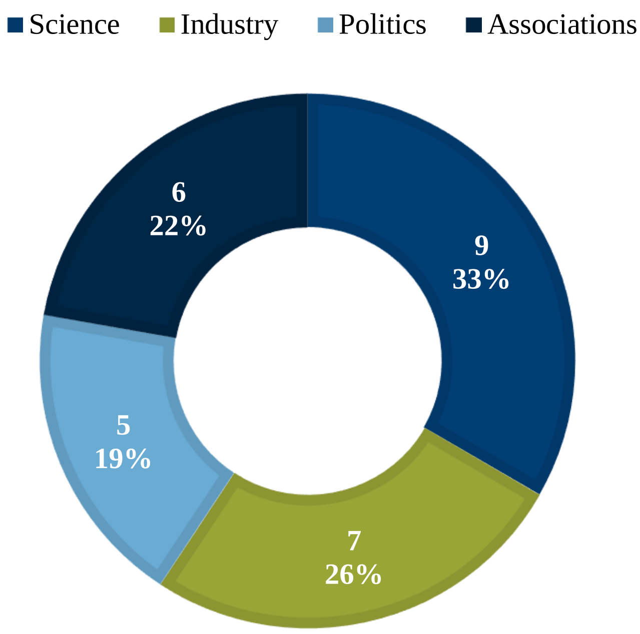
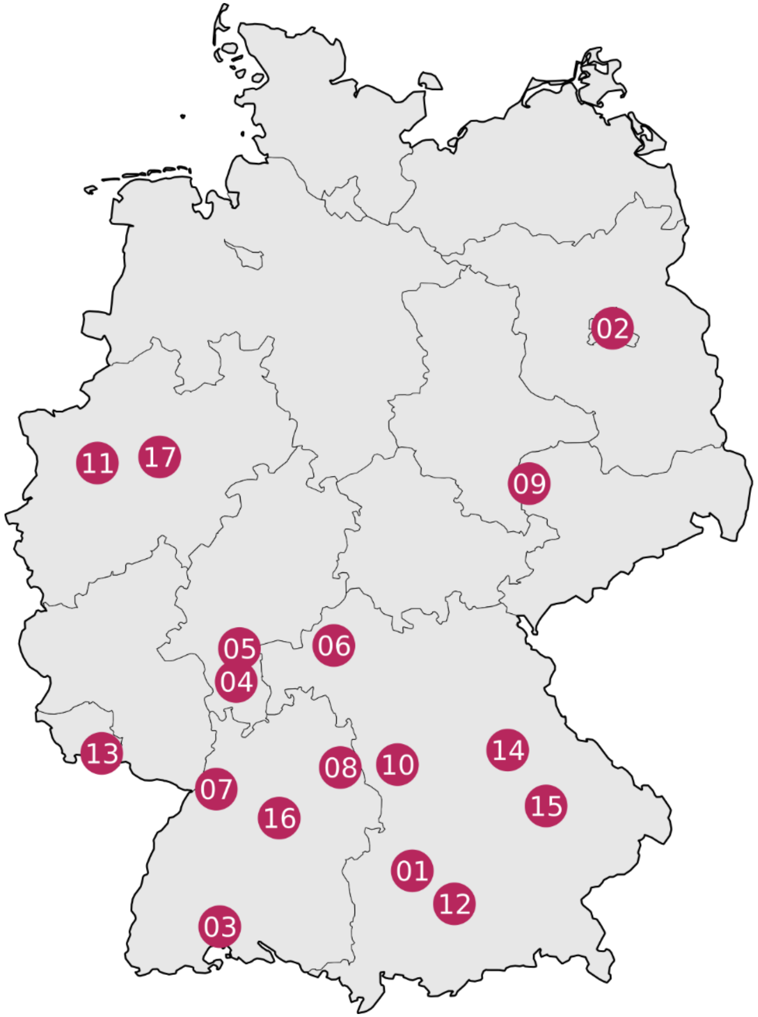


Figure 20. Sectors of the stakeholders participating in this research.

The first three interviews served as a pilot phase, which helped to refine the questions of the interview guide. This data was included in the analysis of the present study. Field notes were taken during and after the interviews, gathering especially background information, non-verbal expressions and statements that were especially highlighted by the stakeholders during the interviews.

4.7 Qualitative content analysis

The term content analysis refers to diverse methodological approaches to examine and characterize qualitative information present in various forms (e.g., audiovisual or scripted), in a structured, objective and measurable way (Crano et al., 2015). With this technique, the researcher studies raw data meticulously and in an ordered manner, outlining the data into subjects, attributes and formats relevant in answering the research questions (Crano et al., 2015). The organized data could also be subject to statistical exploration, generating arithmetic evidence from the qualitative study (Crano et al., 2015).



ID	Location	Number
01	Augsburg	1
02	Berlin	3
03	Bräunlingen	1
04	Darmstadt	1
05	Frankfurt	1
06	Hammelburg	1
07	Karlsruhe	2
08	Kirchberg	1
09	Leipzig	2
10	Merkendorf	1
11	Oberhausen	1
12	Planegg	1
13	Saarbrücken	1
14	Schwandorf	1
15	Straubing	1
16	Stuttgart	7
17	Unna	1

Figure 21. Geographical distribution of the interviewees.

Table 2. List of interviewed stakeholders.

Affiliation	Date of interview
University of Stuttgart – Institute of Energy Economics and Rational Energy Use (IER)	16.01.17
University of Hohenheim – Chair of Biobased Products and Energy Crops	23.02.17
University of Hohenheim – State Institute of Agricultural Engineering and Bioenergy	27.03.17
Stakeholder from science (preferred anonymity)	19.01.17
German Biomass Research Center gGmbH (DBFZ)	19.04.17
International Institute for Sustainability Analysis and Strategy (IINAS GmbH)	30.01.17
Stakeholder from science (preferred anonymity)	10.04.17
Fraunhofer-Institute for Environmental, Safety and Energy Technology (UMSICHT)	26.04.17
Institute of Biogas, Waste Management and Energy	28.02.17
Agrikomp GmbH	31.01.17
Viessmann - MicrobEnergy GmbH	20.04.17
Arcanum Energy Systems GmbH & Co. KG	11.04.17
Schwaben Regenerativ GmbH	24.02.17
Bionova Biogas GmbH	03.05.17
NAWARO® BioEnergie AG	23.02.17
Electrochaea GmbH	21.04.17

Table 2 (continuation). List of interviewed stakeholders.

Affiliation	Date of interview
State Institute for the Environment, Measurements and Nature Conservation (LUBW)	12.04.17
Ministry of Environment, Climate and Energy (UMK)	13.02.17
Ministry of Rural and Consumer Protection (MLR)	22.02.17
Ministry of Rural and Consumer Protection (MLR)	22.02.17
Green Party in Baden-Württemberg	08.05.17
Stakeholder from associations (preferred anonymity)	07.02.17
Fachverband Biogas e.V.	29.03.17
Central Network for Marketing Agricultural Raw Material and Energy e.V. (C.A.R.M.E.N.)	03.03.17
Association of the German Chemical Industry e.V. (VCI)	06.02.17
International Biogas and Bioenergy Centre of Competence GmbH (IBBK)	21.02.17
Biogasrat e.V.	03.05.17

Table 3. Characteristics of the interviewees.

ID	Stakeholder			Interview
	Sector	**Gender**	**Experience (Years) ******	**Duration (hh:mm:ss)**
1	Associations*	Male	8	00:39:58
2	Associations	Female	5	01:46:47
3	Associations	Female	15	01:04:39
4	Associations	Male	8	01:29:29
5	Associations	Male	15	01:25:25
6	Associations	Female	14	00:51:30
7	Politics**	Male	10	01:15:33
8	Politics	Male	9	01:11:09
9	Politics	Male	3	00:41:07
10	Politics	Male	6	01:02:38
11	Politics	Male	17	00:25:01
12	Science	Male	19	00:58:07
13	Science	Male	5	01:34:41
14	Science	Male	15	01:34:49
15	Science	Male	3	00:44:45
16	Science	Male	6	01:30:22
17	Science	Male	16	01:10:19
18	Science	Male	16	01:11:26
19	Science	Male	8	01:17:32
20	Science	Male	15	00:52:21
21	Industry	Male	8	01:05:43
22	Industry	Female	10	00:52:11
23	Industry	Male	10	01:26:17
24	Industry	Male	4	00:38:57
25	Industry	Male	3	00:53:52
26	Industry	Male	9	00:45:14
27	Industry	Female	18	00:27:56
	Sectors: 4***	**Fem. (5) Male (22)**	**Years of experience: 10.19 (avg.) SD= ±4.96**	**Duration 01:04:22 (avg.)**

Legend:

* Professional and consulting groups were included.
** State authorities were included.
*** Science, Industry, Politics and Associations.
**** Inferred from their public profiles, some were directly asked.

Each interview was transcribed in a verbatim form (word-by-word) using the software MAXQDA v12®. More than 300 pages (Font: Times New Roman, size: 12, margins: standard) resulted from the transcription of the audio files. To facilitate and guide the transcription process, a list of rules was defined in advance (e.g., indicate when interviewees accentuated a statement and anonymization of their contributions). The analysis of the data was also assisted with the software mentioned before. This application was used to facilitate reading, editing, coding, annotating, visualizing and ultimately helping summarize the findings of the study.

A code or code unit is an element to be organized in a content analysis part of a context unit. The latter is the frame of reference in which the essence of a code can be obtained, e.g., a whole interview or a paragraph (Crano et al., 2015). Conversely, a category is a concept (e.g., word or phrase) that characterizes a particular portion of the data under analysis (e.g., a thematic group of codes), which derives from an exhaustive coding process (Saldaña, 2016). A code- or category-system supports the researcher to systematically organize its data from which it derives its conclusions, based on common features or patterns (Crano et al., 2015). Such a system is a catalog compiling a list of features that delineate particular observations in the data collected (Crano et al., 2015).

When examining the data and generating codes, the investigator could follow a deductive ("theory-driven"), an inductive ("data-driven") (Crano et al., 2015), or an abductive content analysis ("based on participants´ view") (Bryman, 2012; Kruse, 2014). In a deductive approach, the code system is generated before assessing the data, subject to the analysis of the theory; this way, assumptions derive from what are the "rules", shaping the theme and aims of the investigation (Crano et al., 2015; Kruse, 2014).

Through an inductive analysis, the investigator produces the codes and its structure as the analysis of the data develops, evaluating and adjusting the code system recursively and making generalizations from the observations obtained (Crano et al., 2015; Kruse, 2014). In this study, the author followed an inductive analysis, defining and re-structuring codes and categories while exploring the data collected. Specific observations were assessed, understanding patterns within them, identifying associations between ideas and summarizing the concepts that result from the data collected (Schulz, 2012). Figure 22 illustrates the general procedure for inductive content analysis.

Another approach for qualitative data analysis is the abductive examination. With this technique, the researcher explains the reality as the participants perceive it (Bryman, 2012). In abduction, the empirically obtained data cannot be explained or generalized centered on current theories, generating this way a new guide of interpretation of the world (Kruse, 2014).

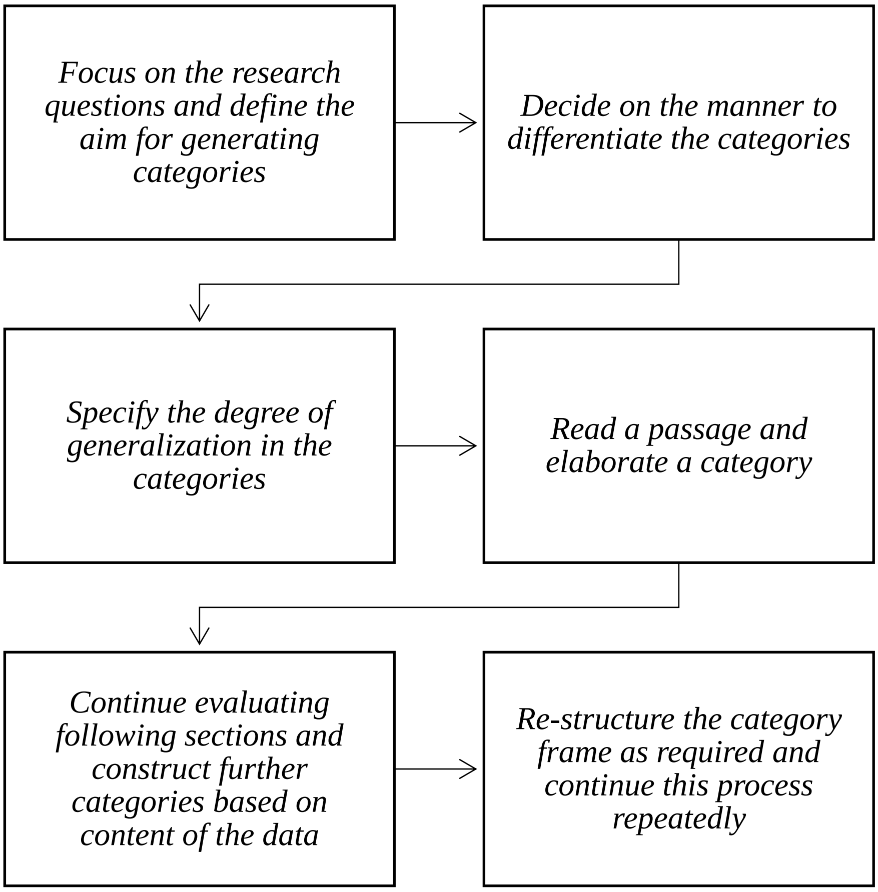


Figure 22. Method for constructing categories inductively.

Source: Kuckartz (2014).

To make possible other researchers to replicate the coding technique followed in content analysis, the methodical approach that guided the coding procedure should be described and registered. In this respect, once the interviews of this study were transcribed, the data was coded, by assigning a brief text to a relevant section to succinct its meaning (Schulz, 2012).

The author followed a two-cycle coding procedure. In a first phase, a "macro-level" or holistic coding approach was used. This is an exploratory method, in which the central message of a passage or piece of study is summarized within provisional codes to large sections of data, depicting its meaning in general terms.

Axial coding is a method employed in a second coding stage, as a means to polish initial coding efforts. This procedure involves a refinement of the code structure, grouping related themes together within a single category and eliminating unnecessary ones. The aim is to refine categories, re-organizing codes and re-classifying them in topical categories (Saldaña, 2016). This approach was firstly described by Glaser and Strauss (1967).

A provisional category tree was elaborated after conducting the interviews and reviewing the notes taken from the field. This structure supported structuring the codes during the qualitative text analysis, an alternative name to qualitative content analysis. The codes were obtained from the data and were ordered within categories and sub-categories, in relation to the research questions being investigated. These categories were then adjusted in the course of the coding and the process of content analysis.

Each one of the interviews was read thoroughly and examined systematically based on a relational analysis model, which consisted in identifying main concepts under each topic and evaluating the relationships between them. Figures 23 and 24 illustrate the assessment method followed in the content analysis of the interviews.

After the interviews were examined and structured within codes and categories, the data was assessed following a topic-oriented approach. With this technique, the author studied the response of each stakeholder based on a specific subject or theme. A thematic qualitative text analysis was followed to examine the data as described by Kuckartz, 2014). In this approach, the perceptions of the stakeholders regarding each topic (code) were summarized per sector, namely science, politics, industry and associations.

This is an appraisal method for examining qualitative data, in which codes and categories are elaborated in various phases and the results of the investigation derive from a theme or category-based interpretation of the data (Kuckartz, 2014). Figure 24 depicts the conventional technique for thematic qualitative content analysis, which was the methodical scheme used in this research. In the first phase, the researcher analyzes the data, marking relevant sections and elaborating a preliminary category system (Kuckartz, 2014).

Then, the data is coded into those general categories, which are produced from the empirical data, comprising the first coding process. Subsequently, the material belonging to similar categories is studied and sub-categories are defined.

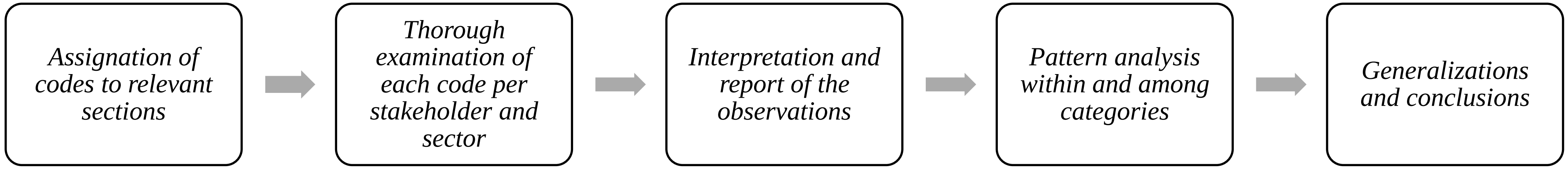


Figure 23. Procedure for the analysis of the qualitative data.

Source: Scheme based on Schulz (2012).

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In a second coding process, the categories are re-structured and classified in detail, based on a further and more detailed coding step until the code system demonstrates profoundness and descriptive capacity (Kuckartz, 2014).

It was possible to create a “profile or thematic matrix” (Kuckartz, 2014), composed by each topic or code (vertically), organized within categories in a superior order and each participant or stakeholder (horizontally), grouped within sectors. This general arrangement is illustrated in Figure 25. There, a sample category “X” is composed of various codes labeled, e.g., from 1 to n. These codes were then analyzed across all stakeholders pertaining to a specific sector “Y”. Once this assessment is performed, the author obtains the conclusions of a category theme pertaining to the sectors represented by the interviewees.

This technique allowed to compare the statements among various groups regarding a similar topic. The meaning of what was being said was interpreted: it was studied how ideas related to each other, the kind of relationships that existed among them, the broad categories and the research questions. This process was systematically and iteratively applied to all interview transcriptions, studying and comparing codes and categories and summarizing ideas. Following this step, the classification tree was then adjusted accordingly.

About stakeholders and measures identified as necessary to manage risks and challenges of implementing PtG in biogas, the author displayed the codes obtained within these categories using the statistical technique of percentage frequency distribution (cf. 5.9 and 5.10) as described by Lavrakas (2008). With this method, it was possible to present the relative predominance of a perceived responsible actor or necessary mechanism, as mentioned by the interviewed stakeholders and as a function of their respective sectors.

A narrative from the data was elaborated, describing the categories from the interviews. Some direct quotes were used to support the arguments presented by the participants but always keeping the anonymity of the respondents. The interrelationship between categories and subcategories were discussed and finally, conclusions and recommendations were derived from the exhaustive analysis of the data collected. In the following section, the main findings of the study are presented in detail, by topic and sector of the stakeholders. Some quotes from the stakeholders are cited in the results’ section. The author translated the stakeholders’ statements from German into English.

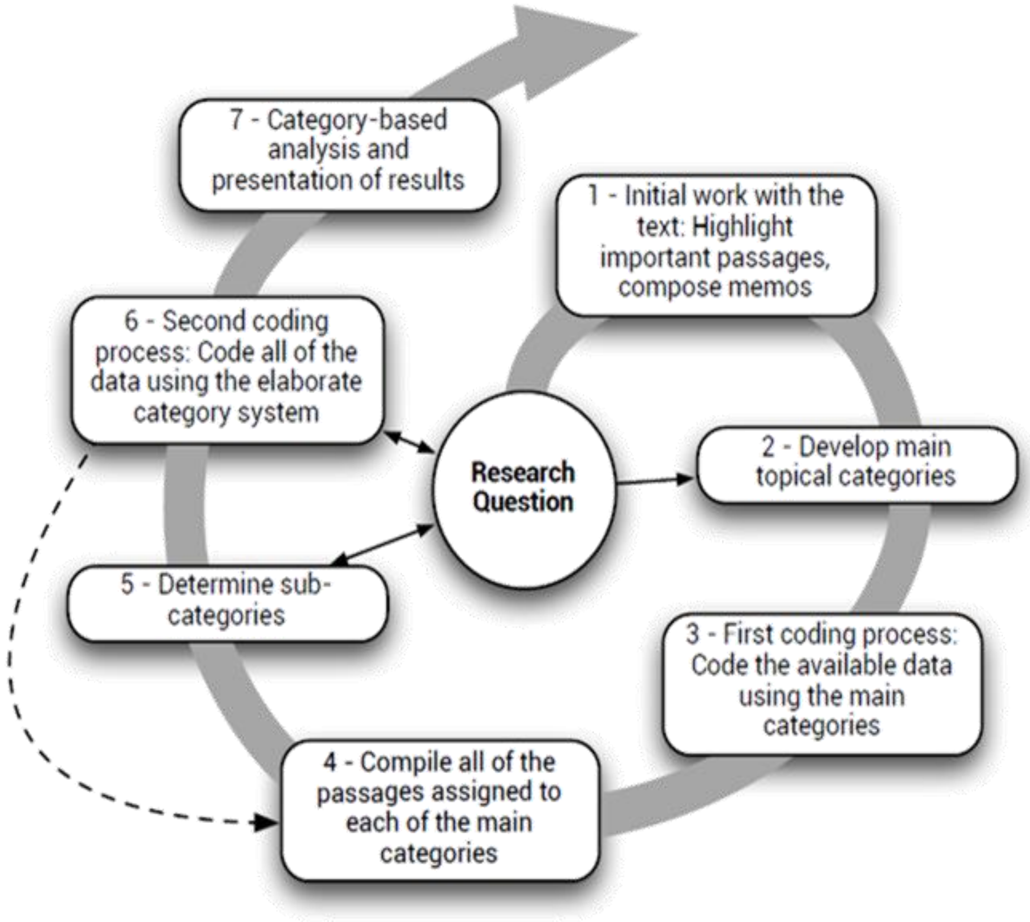

Figure 24. Approach for thematic qualitative text analysis.

Source: Kuckartz, 2014)

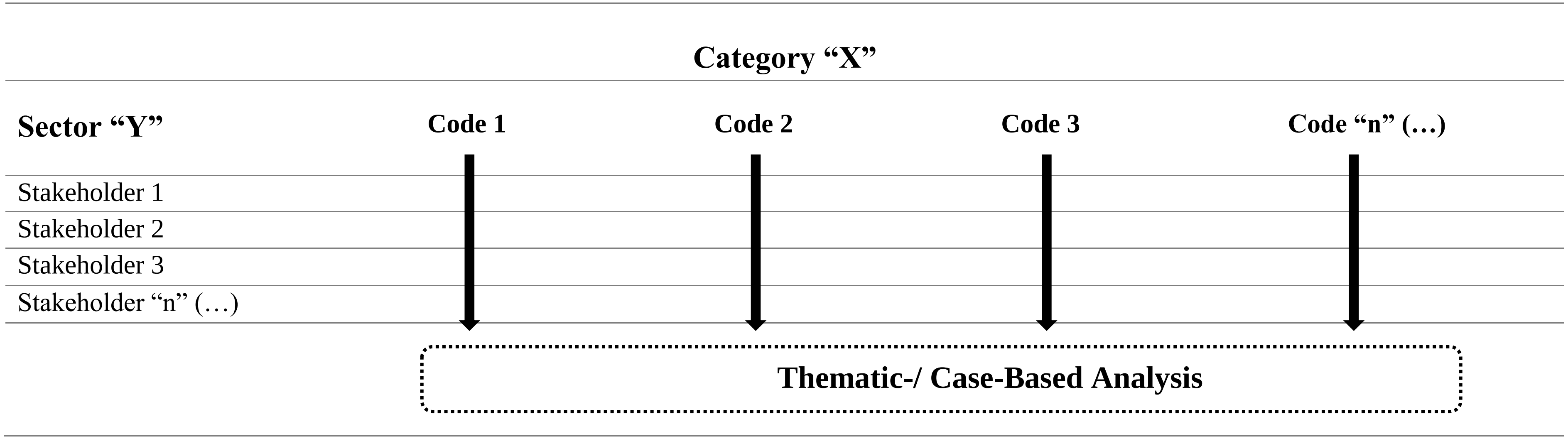

Figure 25. Thematic matrix of qualitative content analysis followed in this study.

Source: Scheme based on Kuckartz (2014).

Chapter 5. Results

5.1 Code system

A description of the code system obtained from the qualitative content analysis, based on a two-phase coding process, is shown in Table 4. Codes were arranged within a structure composed of categories and sub-categories as displayed in Tables 4 and 5. They are presented together with their frequency, which is an indicator of a topic's predominance. The following themes were mentioned the most by the interviewees: “policy measures”, “technologies competing with PtG”, “use of energy plants & demand on land”, “economic feasibility” and “communication & image campaigns”. Category II and III were analyzed in a generalized form since they were complementary to the main topics of the investigation, namely risk perception and management.

Table 4. Outline of the code system’s configuration.

Categories	Sub-Categories	Description
I. Benefits of adopting PtG in biogas		Aspects perceived as favorable in the implementation of the technology
II. Attitudes about using biomethane as a carbon source		Opinions on the innovative use of biomethane as a platform substance
III. Perceived risks and challenges of PtG in biogas		Threats and barriers associated with the adoption of PtG in the biogas sector
	a) Environmental and safety risks	Potential detriment on the ecosystem and fear of accidents
	b) Societal opposition	Topics of possible public criticism
	c) Political difficulties	Government-related obstacles
	d) Technological plights	Technological performance & management
	e) Economic barriers	Uncertainties about profitability
IV. Actors to manage risks and challenges		Identified stakeholders accountable for dealing with threats, obstacles and uncertainties
V. Risk management options & measures to deal with barriers		Actions identified as suitable to handle denoted risks and challenges
VI. Areas requiring further research		Topics of limited knowledge by the interviewed stakeholders, or identified by them as uncertain and of scientific relevance

Table 5. Code system obtained from the qualitative content analysis.

Code Structure			Frequency
Categories	**Sub-categories**	**Codes**	
I. Benefits of adopting PtG in biogas			70
II. Attitudes about using biomethane as a carbon source			97
III. Perceived risks and challenges of PtG in biogas			
	a) Environmental and safety risks		
		1. Use of energy plants & demand on substrate and land	82
		2. Risk of handling H_2 & potential explosions	36
		3. CH_4 and CO_2 releases	24
		4. Emissions via transportation	4
		5. Digestate infiltration	2
		6. Odors	3
	b) Societal opposition		
		1. Not informed & Distortion from the media	17
		2. Criticism & skepticism	71
		3. Generalized accidents	2
		4. No willingness to pay	8
		5. Complex topic	13
	c) Political difficulties		
		1. Opposed political goals: Energy supply & Climate protection	7
		2. Stigmatization of biogas	24
		3. Lobby groups	27
		4. Constant change of regulations	9
		5. Missing political support	50
	d) Technological plights		
		3. Source of H_2 and excess renewable electricity	25
		4. Energy loss in transformation paths	3
		5. Changes in the biogas value chain	26
		6. Technologies competing with PtG	81
		7. Problem of pure cultures	2
		8. Reliability & flexibility	29
		9. Plant management	22
		10. Complexity	16

Table 5 (Continuation). Code system obtained from the qualitative content analysis.

Categories	Sub-categories	Codes	Frequency
III. Perceived risks and challenges of PtG in biogas (continuation)			
	e) Economic barriers		
		1. Economic feasibility & competitiveness in the renewable energy market	89
		2. Energy demanded within the system	22
		3. Acceptance by biogas producers	12
		4. Attitude of the chemical industry	13
		5. Change in the business model	4
		6. H_2 storage	4
IV. Actors to manage risks and challenges			
		1. Biogas producers (incl. farmers and industries)	10
		2. Research institutions	16
		3. Associations (incl. cooperatives)	9
		4. Politicians	51
		5. Banks	2
		6. Media	11
V. Risk management options & measures to deal with barriers			
		1. Communication, information & image campaigns	81
		2. Safe plant management & training	15
		3. Pilot plants & design of business plans	34
		4. Policy measures	120
VI. Areas requiring further research			
		1. Type of political support	14
		2. Environmental service & impact assessment	29
		3. Economic feasibility	19
		4. Technology development	37

5.2 Use of biomethane as a platform substance

Regarding the use of biomethane as a platform substance in the chemical industry, in summary, the stakeholders exhibited concerns about the potential eagerness of people to pay for a premium product derived from biomethane. Besides, there is disagreement about the necessity of political support for this sole purpose. Table 6 shows an overview of the stakeholders' main opinions on this matter.

Table 6. Stakeholders' opinions about using biomethane as a carbon source.

Stakeholders	Attitudes
Science	▪ The majority agrees that people are not keen to pay more for a product just for being labeled as biobased. It should offer something more. ▪ The industry is shifting internally towards a circular economy without any intervention.
Industry	▪ Technically, biomethane is equivalent to natural gas. Thus, it can adequately substitute it. ▪ Currently, there is no political incentive, but it is wished this way. It is believed that biobased products should create a market by themselves. ▪ There is a niche for biobased products; the concern is about how much people would be willing to expend for them.
Politics	▪ Besides having a positive environmental footprint, it is essential that products remain competitive. In the end, it is a matter of price. ▪ Political framework conditions are essential to promote this emerging market.
Associations	▪ Biobased products should communicate their environmental footprint by indicating their standardized examined GHG reduction potential. ▪ To incentivize producers, some suggest politicians set quotas of a minimum share of biomethane in biobased products. An alternative is to have CO_2 certificates. ▪ It is complicated to label a product as biobased since many are a mixture of bio-and fossil-based raw material. Difficulty not only to manage in the industry but also, to communicate with people and develop it as a market concept.

5.3 Benefits of incorporating PtG in biogas

Among the main advantages of implementing PtG in the biogas value chain, interviewed stakeholders mentioned: i) the generation of biomethane with a higher added value; ii) potential for a flexible energy provision from the biogas sector; iii) storage of energy in the already existing natural gas grid; and iv) possibility to reduce CO_2 emissions from biogas installations. Table 7 illustrates a summary of the central statements of the stakeholders, concerning the convenience of PtG in biogas, distributed by the stakeholders' sectors. In the following sub-sections, their arguments are described thoroughly, organized by their public domains.

Table 7. Identified benefits of implementing PtG in biogas.

Stated benefits	Stakeholder*
1. Generation of biomethane for multiple uses (e.g., fuel, electricity, cooking, heating)	a – b – c – d
2. Storage of surplus renewable electricity (flexibility in the energy system)	a – b – c
3. Compatibility with biological processes in biogas, already mastered by producers	a – c
4. Use of excess CO_2 from biogas plants (Reduction of GHG emissions)	a – b – d
5. Potential to use locally available biomass as feedstock for fermenters	a – b
6. Facility to use the already installed natural gas grid	a – b – d
7. Increase in efficiency of biogas installations (higher methane yields)	b – d

*Representation of the stakeholders' sector:

Science (a); Industry (b); Politics (c); Associations (d)

Stakeholders from science

Interviewed stakeholders from science emphasized that implementing PtG in biogas facilitates the generation of biomethane, which has a higher value within the energy supply chain. They indicated that this product provides more use flexibility, e.g., as chemical energy storage; it could be used as a fuel in the transportation sector; or for electricity generation; for cooking; or heating.

They explained that surplus energy from wind and solar power, which now is being wasted, can be stored with the assistance of PtG. They specified that this innovation in biogas could function as a service provider, stabilizing the supply of renewable energy: storing it when there much produced or generating it when there is not enough available. They insisted that this service need to be acknowledged and remunerated. Although, the interviewed stakeholders from science indicated that this advantage should be considered relative to competing technologies, e.g., other power-to-x options.

In this line, they reiterated the benefit of using the existing gas network, to which many biogas plants have access. They explained that the already installed natural gas network could be used as a means of storage. Thus, there is no need to make expenditures on additional infrastructure. Furthermore, this gas network would allow an independent provider of biomethane, decoupled in time and space. Another benefit of PtG identified by experts from science is that the technology fits with current biological processes in biogas, which producers, e.g., farmers, are well familiar. They said that this factor could facilitate its insertion in the market. As one interviewee put it:

"We know biogas plants and one knows how it works. Now there is an additional tank or reactor and it fits the other components in biogas."

Finally, stakeholders from science marked that PtG helps use excess CO_2 from biogas plants, which they pointed out, corresponds to around 40% of all the gas produced. This way, not only GHG emissions are reduced, but also, the biomethane yield can be increased. Besides, they are confident about the potential of PtG to use locally available feedstock, which could assist to reduce any negative environmental footprint and the complexity of the system.

Stakeholders from industry

For some experts in the industry, the main benefit is related to the increment of the efficiency of biogas. They expressed that the biogas value chain is improved by converting energy into primary energy sources: H_2 and CH_4; these products can then be used in different fields, what they called “sector coupling”. Several uses are available having biomethane as a product and energy carrier. They highlighted that this aspect is significantly advantageous in comparison to other storage technologies like batteries.

Likewise, interviewed stakeholders from industry distinguished a positive environmental effect from biogas in association with PtG, because from the same amount of substrate the PtG technology potentials to generate more methane. Thus, it is anticipated less land to be demanded in biogas under a PtG model. Moreover, they indicate that from this synergy between biogas and PtG, cheap CO_2 will be available, which is currently wasted. They indicated that by the implementation of an electrolysis reactor, this excess gas could be converted into a valuable product: biomethane.

Another aspect mentioned by stakeholders in the industry is that through the implementation of a PtG concept in biogas, there is less dependency on fossil fuels. They argued that this technology helps decarbonize the economy, e.g., in the mobility or the chemistry sector, in which CO_2 emissions are avoided by substituting fossil raw materials with renewable biomethane.

Further, stakeholders from industry emphasized that the gas generated can be stored directly into the existing infrastructure of the natural gas network. They are confident that there is no need for additional investment for constructing storage lines. Furthermore, using the gas network, the deposit capacity is extensively more significant, as in contrast with other power-to-x technologies. They indicated that as part of the biogas sector, PtG could ensure that renewable energy is available as a function of the demand, linking this aspect directly with the flexibility of the energy supply.

Stakeholders from politics

Largely, contributors from politics perceived PtG as a significant benefit in combination with available biogas plants. They stressed that biomethane could be produced in a demand-driven base and to the quality of natural gas, allowing its same uses. Stakeholders from politics also accentuated that biomethane as a product can be used universally, in contrast with biogas, which they described, technically can only be used on-site. Moreover, they pointed out that biogas is well-known and well spread, making it easy to implement PtG in practice.

Interviewees from politics accentuated the potential environmental benefits of using exhaust CO_2 from biogas plants for the generation of biomethane. They expressed that this environmental-protection concept sounds quite attractive to them. Furthermore, participants from politics have high expectations that PtG helps reduce the demand on land from the biogas sector and the amount of substrate required to produce biogas and ultimately, biomethane. They emphasized that this possibility would have not only significant environmental effects but also an economic significance for biogas producers.

Some experts from politics judged PtG to be a simple technology and relate it to the known biological process, part of the already mature biogas production. They argue that PtG is not complicated because it requires microorganisms, already available in biogas digesters and uncritical operating conditions, except handling H_2. Besides, through BM a hygienization of the fermented substrates is also obtained, a topic highly emphasized by the stakeholders from politics.

Nonetheless, some show participants in this sector displayed skepticism about a detailed technical and economic feasibility of PtG. Some experts from politics expressed uncertainty about the possible benefits of having PtG in biogas because so far it has been discussed based on theoretical concepts and with only a few pilot plants. Therefore, some have reservations to rely on the promises of this innovation at its current stage of development.

Stakeholders from associations

Stakeholders from associations underline that the most substantial benefit of integrating PtG in the biogas value chain is that long-term energy storage can be achieved and energy can be provided in moments of high demand and vice versa. They conceptualize that the resulting biomethane can then be stored in the natural gas network, from which it can have multiple uses, e.g., electricity, heat, transportation, as a fuel, or also as an input material for the chemical industry. In their line of argumentation, stakeholders from associations hypothesize that by using the existing gas network, PtG opens the possibility for broader geographical distribution and application of biomethane. It means that the gas can be brought everywhere and converted into different forms on-site. For example, one interviewee said:

"With BM [as a PtG concept] in biogas, the electricity production can be timely decoupled because the biomethane can be deposited in the natural gas network. Then, it can be used in various economic sectors."

Much like other stakeholders, some participants from associations pointed out that PtG offers a positive climate protection effect by helping reduce CO_2 emissions from biogas plants. By combining excess CO_2 with H_2, the biomethane production can be incremented with PtG. Upon that, they compared BM with the catalytical methanation and concluded that the former is less sophisticated and expensive, demanding a reduced amount of materials.

However, some experts within this sector criticized the reasons for using excess renewable energy in a PtG concept. Some stakeholders from associations are still not convinced if it makes sense to implement PtG in the biogas sector. For those stakeholders, the meaning would derive from a cost-benefit lead, which PtG has not yet demonstrated. They stated that whenever a remarkable revenue is achieved, then it is wise to deploy the technology. Stakeholders from associations also valorized PtG as especially interesting, only under the condition that it could be scaled for smaller biogas plants since they consider there are only a few technological options for modest biogas installations.

5.4 Environmental and safety risks

Stakeholders from science

Various participants from science affirmed that previously, multiple accidents from biogas plants occurred throughout Germany, which generated significant adverse environmental impacts. They stressed that those incidents happened due to deficient biogas installations. Participants from science stressed that those small facilities need to be improved before any innovation like PtG is implemented or must be removed entirely to avoid further harmful episodes. For example, one interviewee from science said:

"There are very many examples especially in Germany, where it [biogas] has gone wrong; it had a bad environmental impact and we must get rid of that. These plants must change."

There was a prevailing perception among stakeholders from science that the environmental footprint of biomethane production will be improved by installing PtG in the biogas. Nonetheless, they expressed that the cultivation of biomass as a renewable plant will remain as before since the biogas process would require energy plants to generate biomethane. Despite this latter condition some of the interviewed stakeholders from science conceive PtG as a chance for the biogas sector and not as a risk. They assessed the PtG technology on the assumption of employing organic residues as feedstock for the generation of biomethane. In this line, stakeholders from science expect no additional land demand to grow biomass as input material for the biogas process connected with PtG.

For many stakeholders from science, potential risks from biogas and PtG are mainly of environmental nature. In this regard, they considered that PtG does not pose any risk in combination with biogas, because it will help the biogas value chain to reduce its environmental impact. Some interviewees from science explicitly mentioned that they do not foresee any considerable detrimental effect on nature than that existing nowadays from biogas installations once PtG is implemented. Only some interviewees from science highlighted to be cautious with methane leakages because of its GHG importance. They explained that gas leakages are a problem confronted in current biogas plants, which is a constant environmental risk that needs to be tackled.

Stakeholders from science insisted that biogas facilities need to be designed in a way that fugitive emissions are avoided, as one interviewee put it:

"I do not see any extended environmental harm [from installing PtG in biogas plants]. For sure one is working with methane, which has a high risk of global warming potential if it is released it into the environment. However, this is true for already running biogas plants. Thus, one must take care that those plants are tight. [I believe] this issue will remain to be an important challenge in biogas installations. Apart from that, I do not see any additional negative environmental impact."

On this subject, most stakeholders from science ascertained that in case of any environmental externality due to gas leakages from biogas installations, it could be managed merely using existing safety techniques. However, these stakeholders indicated that gas emissions from PtG-biogas installations could nevertheless become a topic of controversy in German society. One participant from science expressed:

"Methane slips could still be an issue, but I think one can control it technically."

Similarly, in case of accidents, some stakeholders from science considered that biogas producers already had gathered sufficient experience managing their biogas plants and because of that, they could easily handle this new H_2. Several participants from science indicated that the environmental risk would be only slightly higher, but nothing to worry.

Regarding the potential impact of electrolysis on human health, some participants from science unrelated to the biomethanation process to any potential radiation or adverse effects on the wellbeing of people. However, one interviewee from science explained that hydrogen reactors generate a lot of very high-density electric and magnetic fields, which could be dangerous to human health. They indicated that this situation represents a high risk when linking the PtG technology with biogas.

Concerning environmental risk management, some stakeholders from science classified biogas operators in Germany into two groups: 1) those who follow in detail the security regulations and 2) those who merely follow the standards only in the areas in which they know there may be higher risks of explosion. Overall, stakeholders from science accentuated that if biogas producers would bind to existing safety rules, then, possible problems could be solved, such as risks of potential accidents or any environmental harm. For example, one interviewee from science said:

"The question is: do we want 100% safety? I think Germany regulations have become stricter over the last years because there were some incidents in biogas plants. Maybe after the accidents, the responsible said: ok, we must intensify the regulations and maybe take care that producers reduce the risk of accidents in their plants. I think the type of biogas operators is heterogeneous [in Germany] and many of them bind to the regulations. However, many of those producers are more pragmatic and only take care of the most important regulations, but not all in detail. I believe that if plant operators take care of safety regulations, risks could be minimized."

In principle, stakeholders from science believe that existing technical standards are sufficient to avoid any potential risk of explosion or environmental pollution. In this regard, participants from science believe that safety issues would not represent any problem to manage. However, they expressed environmental and safety risk management would be feasible only for large biogas plants, where there is trained personnel. Stakeholders from science believe that in small biogas plants there is a higher risk of accidents, some showed concerns about implementing PtG in small biogas installations, due to inefficient safety measures. They emphasized that these risks should be minimized by promoting safety procedures among the staff of biogas plants. As one interviewee from science said:

"I would say that the safety standards are mature and manageable in Germany. I think it will be less of a standards' problem. The solution lies in having trained personnel in the plants. With smaller plants, I would have a bit of trouble installing such a system of PtG."

Some participants from science considered that it is essential to assess from which plant size it would make sense to install the concept of PtG. They indicated that from the 8000 existing biogas plants in Germany, many of them are operated by farmers, which are as they categorized them as "self-made" installations.

For stakeholders from science, such facilities represent a real safety risk, because there is less technical know-how available. Furthermore, various stakeholders from science indicated that practically in every technology there is a risk of an accident. In biogas it has been experienced, e.g., when a digester exploded or with infiltration to groundwater. These cases cannot be denied; they indicated; however, they mentioned that these are only particular cases, as almost all technologies generate environmental impacts.

Stakeholders from industry

Overall, participants from industry believe that maize should and will be displaced entirely to produce biogas and its derived products. They emphasized the need for alternative carbon sources for biomethane production, such as organic waste and agricultural residues. Stakeholders from industry justified this opinion, saying that the current sociopolitical attitude towards maize in Germany is inherently damaging. It was evident among these stakeholders that instead of acknowledging any previous environmental impact from the biogas sector, as interviewees from science did, participants from industry considered slightly social pressure as the reason for the search of alternative feedstock to run biogas plants in connection with PtG.

The following is a statement of a stakeholder from industry, which exemplifies the attitude of these participants on the feedstock matter:

"I think the demand for substrate will tend more towards waste and agricultural waste. Energy plants will be reduced a bit; I believe because of social pressure and because of the [associated production] costs. Politicians have already set the course so that more residual materials are used. Now, one has to see if these substrates are sufficient for the CO_2 demanded in BM [as a PtG concept]."

Because of this shift in the type of input substrate, from maize to manure and biowaste, many stakeholders from industry expect no adverse environmental effect from the technology. Besides, they rely on the existence of efficient safety and environmental protection regulations in the country, which will in time, avoid any possible accident or environmental harm. Furthermore, some participants from industry indicated that they do not perceive any risk of land-use intensification to source CO_2 for biogas production in connection with a PtG concept.

They considered that in case of an increase for land-use to grow energy plants, many regulatory measures and instruments had been developed in Germany, which controls any undesirable event emerging from the biogas sector. Stakeholders from industry assessed a somewhat positive environmental effect from biogas, based on specific evidence they have consulted, in which it is projected a significant biomethane yield increment, derived from the implementation of the PtG technology (cf. 5.3, stakeholders from industry).

Some stakeholders from industry understand that previously discussed environmental impacts from biogas were merely political discourses in disregard of the biogas sector and to favor specific business groups. Interviewees from industry expressed that statements such as “Vermaisung der Landschaft” (visibility of extensive maize cultivation in the landscape) or the “Teller-Tank” discussion reflected how politicians are influenced by particular lobby groups, such as the coal industry; deteriorating this way the image of the bioenergy sector for their benefit. Moreover, several stakeholders from industry repudiated people’s criticism of the biogas sector, indicating that their criticism was not proved. Participants from industry were convinced that they have technological risks under control, such as potential explosions by handling H_2 in a concept of biogas and in connection with PtG since they perceive H_2 as a non-dangerous gas.

Talking about this issue, an interviewee from the industry said: *“H_2 alone is unspectacular since it is not a high-energy carrier in comparison with gasoline or natural gas. Therefore, I do not perceive it as a hazardous gas. Of course, it reacts with some substances, but the risk of explosion I would express is controllable. I think like this: low energy carrier equals low risk.”*

Stakeholders from industry believe that conventional safety measures for handling flammable gases will continue to be used in Germany; because of that, they perceive no to low risk of explosion in biogas installations connected with an electrolyzer of a PtG concept. Additionally, some stakeholders from industry considered that because H_2 will be mixed with CH_4 along the biomethanation process, the risk of an explosion would be reduced. On that amount, the demand for safety issues would not be too high in PtG-biogas installations. In general, these stakeholders believe that if existing safety requirements in Germany are followed, there is no need for any additional risk management measure for installing PtG within the biogas sector.

Some statements of stakeholders from industry reflecting their position on the safety issue are the following: *"I expect that the typical technical safety measures that exist in Germany will continue to be used. Therefore, I do not expect any risk of explosion." Another one: "I expect no major special safety requirements [for a PtG concept in biogas] because the [conventional] raw biogas has relatively high methane content, which is also combustible. I do not think there will be any significant safety condition if one now increases methane levels even further."*

Similarly, stakeholders from industry considered that risks of explosion or accidents are higher in traditional biogas plants than in the concept of PtG. The argument they postulated was that they believe in many farm-based installations technical know-how is not available and the safety measures are not thoroughly followed. Therefore, more accidents can happen. Overall, interviewed stakeholders from the industry suggested that PtG plants should be designed for high-scale/industrial sizes, in which trained personnel operates the facility.

Stakeholders from industry indicated that if biogas plants with a PtG concept are managed in an unprofessional matter and operators elaborate their plant concepts without the appropriate safety measures, then, essential risks could emerge. As one interviewee from industry put it: *"PtG plants are industrial constructions equipped with all safety technology so that nothing [no accident] happens."*

The perspective of some participants from industry is that these PtG plants will be constructed based on the state of the art of the technology. In this regard, they believe that all security measures necessary for approval will be followed, which will eliminate any potential risk. A danger that some stakeholders from industry did mention was the hazard of no complete hygienization of the fermented material if the PtG technology is complex for biogas farm operators. Participants from industry advised producers should also know how to run the plant in connection with the electrolyzer in a PtG concept, e.g., how to start and stop the process.

In contrast, interviewees from industry expressed that in high-tech plants this complexity would be less of a problem because they have the know-how and the technicians who are trained to solve any inconvenience. Some participants from industry considered that specifically, biogas plants run by farmers have critical weaknesses regarding safety and management.

In general, stakeholders from industry expressed doubts about how tight farmers close their reactors, which could influence gas leakages generated. Because of that, some participants from the industrial sector perceive biogas as much more dangerous concerning gas emissions as the concept of PtG for industrialized plants, which they anticipate will follow strict safety measures.

Stakeholders from politics

Like the previous stakeholders, participants from politics believe that there will be no environmental impacts in biogas, derived from the implementation of PtG in its production scheme. If there could be any, stakeholders from politics understood that those incidents would be easily manageable. For example, one interviewee from politics said: *"I see environmental impacts comparatively [to the current situation] as unproblematic. You can get a grip on [any situation that may arise]. Therefore, I do not think that there are big or uncontrollable environmental impacts to be expected. What would be to be feared?"*

Some participants from politics expressed that by implementing PtG in biogas plants, the potential environmental impacts [on water and air] will be uncritical. Various interviewed stakeholders from politics were convinced that those environmental externalities of the biogas production would become somewhat less if PtG is introduced. Considering the existence of regulations that limit the size of the plants and the quality criteria for the hygienization of the digestate, some stakeholders from politics believe that any environmental harm is under control.

Participants from politics had the opinion that low to potentially no detrimental environmental effects will derive from biogas and PtG plants. They argued that excess CO_2 from biodigesters is being used to increase the methane production; however, some participants from politics believe that biogas plants will continue to be run as traditionally, fed with maize silage. Several interviewees from politics doubted the possibility of any substrate substitution for the generation of biomethane.

Some of these participants identified few of the multiple previously appointed problems in biogas and indicated that they could continue, e.g., emissions of nitrogen from the application of digestate and the emanations of GHG from gas leakages.

Like previous interviewees, several stakeholders from politics considered that PtG would be an option for high-tech biogas plants. They explained that operators who already produce ad store biomethane and cooperate with the gas industry would have already experience handling H_2, so they do not foresee any risks of explosion or accident. However, about farmers operating traditional biogas plants, participants from politics expressed that the PtG technology would not be an option for them; they justified that by saying that farmers are not technically specialized. As an interviewee from politics put it:

"For classic farmers, with cows and traditional agricultural production and who additionally has a biogas plant, this [PtG] will certainly not be an option. This technology would be a topic rather for specific plants, working at an industrial scale."

In the existence of hazardous materials from these installations, some stakeholders from politics considered that it is best to concentrate such substances to better deal with them, instead of having such threats in a decentralized way. For participants from politics, this means to have large biogas plants instead of multiple decentralized ones. Also, they expressed that the compliance with strict requirements in the management of hazardous agricultural residues is only profitable in large biogas plants.

Stakeholders from politics suggested finding an appropriate balance between the requirements to treat biowaste and agricultural residues and the size of the biogas plants, demanding a certain amount of waste, some of which should be transported. They stressed that from the transportation of substrates some GHG emissions are being generated, which in many LCA is not sufficiently considered since substrates are mainly assessed on their energy content. Because of this issue, some interviewees from politics believe that waste-based biogas plants should be kept small so that the demand for transported biowaste is also low.

Moreover, interviewees from politics explained that the transportation distance usually does not play a prominent role in the total environmental assessment of biogas plants. Some of these participants discarded the idea of biogas installations needing long transportations for substrate because if so, they would generate significant negative indirect impacts, e.g., noise, which molests people. Nevertheless, participants from politics in general discarded any possible harmful effects of GHG emissions by transportation of manure and biowaste from long distances for biogas generation.

Stakeholders from associations

Some of the environmental effects linked to biogas mentioned by stakeholders from associations were spillage of digestate, contamination of surface and groundwater, gas leakages due to improperly sealed tanks, emitting, e.g., CH_4, noise generation, odor emissions and the detrimental environmental impacts from the extensive cultivation of energy plants.

Overall, stakeholders from associations understand that the problem in the biogas industry is not necessarily linked with the status of development of PtG, but on the use of defined substrates. They indicated that maize is an ideal input material, but it is contested. Contrarily, manure could be more environmentally friendly versus energy plants; however, they emphasized that it has much lower energy content. Because of that, some participants from associations underlined having a substrate mixture between energy plants and residues, like manure.

Moreover, interviewed stakeholders from associations indicated that it would be challenging to renounce entirely on energy plants. The general opinion of participants from associations was that energy plants are a meaningful resource for the biogas production since they are renewable and continuously available. Furthermore, they accentuated that maize is used not only for biogas production but also for the animal husbandry, so they advocated that its use and misuse should be judged for both sectors.

Continuing this topic, interviewees from associations mentioned that the substrates' problem is instead an agricultural issue and not necessarily from the bioenergy sector. They described that biogas producers directly must implement sustainability criteria for their cultivation, which they ponder is an essential aspect of the progress of this field.

Participants from associations judged current regulations of capping the use of maize to only 50% as a limitation for the biogas-biomethane sector. When talking about this matter, an interviewee from associations said:

"What annoys me is that I find NAWAROs [energy plants in English] convenient to use bio-energetically. These are raw materials that are unrestrictedly available since they grow continuously; however, it is essential to adhere to sustainability criteria."

"[…] We reject the political regulations, such as only allowing a share of 50% corn or whole plant silage. We refuse such interventions because they increase the cost of the entire biogas-biomethane production process."

Among the participants from associations, there was an understanding that not only biogas as a type of bioenergy provokes a negative impact on the environment, but that each human activity has a kind of effect. Thereby, since several stakeholders from associations perceive the bioenergy sector only as one small section in the whole "raw-material" value chain, they advocated for the establishment of sustainability standards for the whole agricultural production. They expressed that these criteria should be all-encompassing, considering both animal husbandry and agricultural biomass production.

Some participants from associations explained that they were aware of specific mismanagement linked with biogas in the past, like the transformation of former grasslands for maize cultivation and the destruction of humus in the soil, which they expressed does not allow a positive CO_2 balance through energy plants. Because of that, some stakeholders from associations emphasized that it is important to notice such actions and correct them before introducing any new technology in the biogas sector.

For this reason, some of these interviewees from associations believe that through the implementation of the concept of PtG in biogas facilities, indirect environmental effects will remain unless there is an improvement in the biomass and plant cultivation management. These stakeholders agree that many of the environmental problems related to the biogas sector will remain even after incorporating the concept of PtG if a safe plant mechanism is not implemented and sustainability measures are not considered.

Participants from associations have the conviction that PtG alone will not remove all identified environmental risks in the biogas sector, by installing an electrolysis reactor as part of the PtG concept. They stressed the need to apply direct measures to avoid future complications.

As an interviewee from associations puts it: *"I see the BM only as a second piece, which is incorporated into a biogas plant. Those environmental effects that happen currently in biogas installations will continue to happen unless something in the plant management is changed."*

Some stakeholders from associations considered farm-based biogas plants as especially problematic. They argued that farmers are not careful with the plant management, like when keeping inappropriate gas-sealing constructions and not taking care to avoid odor emissions.

For example, a participant from associations said: *"I feel like there are two types of biogas plants: one is the type built and run by any large corporation and that is being monitored in some way. Risks here are technically solved quite well in my eyes [...] and then, there are still many small biogas plants operated just by a farmer, who does not see the whole thing as a technical system and who has no neighbors, who are bothered by the smells due to sulfur compounds. Those things do not trouble him. You can now I imagine what could happen if an electrolysis reactor is installed there [...]"*

Another type of risks mentioned by stakeholders from associations is that there may be companies trying to sell a product or a technology to farmers with biogas plants, who are not trained enough to manage such a complex concept, such as PtG, or who do not have a safe plant to install such a highly complex concept. As a stakeholder from associations expressed:

"These are vendors, already spread throughout Germany, who are unserious and unscientific. They tell for example to a farmer: yes, if you incorporate hydrogen [into your production], then you can increase your methane yield."

5.5 Societal challenges

Stakeholders from science

Some of the interviewed scientists expressed that a significant risk in the implementation of the PtG technology is the non-willingness of people to pay the costs involved in the biogas and biomethane production. They remarked that people are not ready to pay higher electricity bills "just" (as emphasized by the stakeholders from science) because biogas producers need to be supported.

Therefore, stakeholders from science understand that for the PtG innovation to prosper in association with the biogas value chain, it would need the intervention of politicians to influence the attitude of people towards biogas. Some participants from science indicated that there might be people ready to support the biogas industry and consume the comparably more expensive renewable energies.

However, the interviewed stakeholders from science expressed that those social groups would not be enough to generate a large or visible change in the German context. As one interviewee from science put it:

"Of course, there are also people who would be prepared to pay higher prices for biogas or renewable oil, as for today's electricity too. However, I do not know if they alone can influence much [to promote biomethane]. I think you must help a bit with a legal framework."

On this matter, several stakeholders from science expressed concerns about any possible political intervention to facilitate biogas acceptance and promote people's willingness to pay. In the eyes of these stakeholders, politicians lack the interest to support the biogas sector, which could influence any technology associated with the field.

Despite this worry on politics and uncertainty on people's readiness to consume premium methane and the various derived products, several of the experts from science believe that even without political action there will be a transformation in the industry in overall. Those participants from the science sector supporting this latter idea argue that business people have realized that in order to adapt to current people's demands, their business models must close loops instead of remaining linear. These models must be environmentally friendly and not fossil based, part of a circular economy.

Therefore, some stakeholders in science believe that environmental awareness is growing in the industrial sector, which will generate a shift in mindset, even without political intervention. This change in the industry, say several experts from science, is triggered by people's demands towards more environmentally friendlier products. Talking about this issue, an interviewee from science said:

"I think there will be a shift where the [biogas] industry realizes that their business models are threatened and if it is not accepted anymore by the public. I think, then, there will be a change. [That renovation will happen] even without political pressure. It will be slower, but it will happen, at least in some areas [of the biogas industry]."

Within the science sector, there were, however, stakeholders who had different opinions about people's readiness to support an upgraded biogas derived product. Some participants from science do not expect people to increase their willingness to pay for more expensive goods, just because they are advertised as biobased or are labeled as green. They indicated that, if these products are increased in price, then, it should be something different, or at least it should be clearly stated. This way, people are conscious of the additional feature or service they are paying.

Moreover, stakeholders in science believe that PtG in biogas is still quite a complicated matter for many people to understand. They elucidated that the society at this time does not clearly understand the differences between biogas and biomethane and its contribution towards a more sustainable way of living. This situation happens because either they do not spend much time trying to understand the technology, they are from other backgrounds, or they are just not interested in the topic.

Some of the experts from science considered that PtG will not necessarily change people's negative perceptions towards biogas in a radical way, at least not now. Various participants from science construed that PtG will be inserted in newly built biogas plants and not in existing ones. Since they foresee only a few new biogas installations, the PtG technology would not have an enormous impact on the biogas sector and people's opinions.

Additionally, some stakeholders from science indicated that the criticism on biogas from the population arises because people think that they do not profit from the biogas sector. Overall, participants from science believe that the public see incentives given to promote the biogas industry only as a profit for farmers and some companies to generate money. In this line, it was also common among these stakeholders the belief that people simplify the biogas case, especially generalizing incidents in the field.

Furthermore, some of these participants from science were not entirely sure if people differentiate between the traditional biogas plants and the upgrade version with PtG. They expressed that biogas and biomethanation are complex topics and people do not know the difference between one and the other. Experts from science emphasized that a solution to solve these problems would always be informed, however, some showed hesitation to such a kind of advice, which they categorized as too simplistic.

Various of these stakeholders expressed that researchers already do a part providing knowledge, however, to recommend that “more information is needed” is perceived by various experts from science to be an over-simplification of how to deal with biogas.

Another interpretation of stakeholders from science, explaining people's attitude towards biogas was that the public develops a perception out of criticism from the media. They also believe that the public is generally misinformed due to false information being supplied to them. It was believed by several participants from science, that many accidents in the biogas industry are highlighted by the media, which then remain in people's minds. However, the rest of the story, about the benefits of biogas, is not publicly presented. Moreover, some interviewed experts from science believe that there is false information being distributed among the population, negatively influencing the field. They indicated that contrary and false news commonly spread quite quickly and are easily accessible to the people, believing thus that the population usually is not well informed. The following extract reflects this belief of stakeholders from science:

“Most of the time only worst cases are presented in the media, especially those related to catastrophes and accidents. These cases stay in people’s memories […]; the rest [the positive effects] are sporadically seen […]. Journalists always pick examples in which biogas is doing relatively poor. An objective presentation of the technology is rarely reported in the news.”

Stakeholders from industry

Like some experts from science, several stakeholders from industry considered that people do not know how biogas works and only provide generalized statements such as: “biogas stinks” and there is a “maize monoculture (Vermaisung)”. Participants from industry emphasized that people need to understand what biogas means regarding climate protection and energy supply. Moreover, experts from industry believe that PtG is not broadly discussed in society. They exemplified that biomethane, which has already existed for a while in the German market, is still not wholly assimilated by people as an environmentally friendly alternative to natural gas.

Despite this lack of awareness in the population, some interviewed stakeholders from industry are optimistic about the potential positive reception of PtG, once people gain knowledge about the benefits embedded in it.

Experts from industry expressed that people will accept PtG as an innovation in biogas, if they are explained about the biogas and PtG environmental protection role, their functions closing loops and storing excess electricity. The comment below shows the opinion of a stakeholder from industry on this matter:

"Socially, I believe that it [PtG] already appeals, one needs to express that we are using all material flows, recycling and trying to save energy. I believe that if the [biogas] facilities are safe, we will not get any [disproof] problem [in the population]."

Few stakeholders from industry expressed that the society neutrally sees biogas: neither positive nor negatively. Various stakeholders from the industry said they noticed biogas has a negative image in society (cf. 5.4, stakeholders from industry); however, they explained that this has nothing to do with BM or PtG. As one interviewee from industry put it:

"This perception of biogas plants will certainly improve if there is a PtG plant connected on-site. Biogas plants have a bad reputation [in German society], because of the "Teller-Tank" discussion, monocultures, use of digestate as fertilizer and so on. That is the bad call of biogas, but these topics or problems are not related to the technology of PtG, as a BM in biogas."

In this regard, various participants from industry believe that the perception of biogas will improve in society if PtG is incorporated in its value chain. The main argumentation from stakeholders from industry was that PtG uses excess CO_2 from biogas to increase the share of biomethane when currently CO_2 is emitted into the atmosphere. Considering this aspect, experts from the industry expressed that people will see that there is an improvement from an energetic and material point of view in the biogas sector. Correspondingly, once this concept is understood, participants from industry believe that PtG can generate a "positive attitude" in the people and this way, it can help improve the legitimation of the biogas technology.

Some participants from industry considered that there could be possibilities for biogas to be politically supported again. Nevertheless, they emphasized that biogas needs to be first endorsed in society and the media can play a relevant role in that process, they stated. Then, politicians will follow, as believed by stakeholders from industry and the framework conditions will be established.

Interviewed partners from industry, in general, agreed that for a business model to prosper, the society should first accept the PtG technology and have a demand for biogas, its products and services. These participants are confident that in the future if there is no other storage technique, biogas as a PtG mechanism would be an excellent alternative for energy storage and then, all political conditions will be available.

Several stakeholders from industry indicated that awareness about the PtG technology should be incremented in society because this innovation is not well known in society. For these stakeholders, it is however essential, to differentiate between the traditional biogas production vs. biomethane with PtG. However, experts from the industry indicated that regarding communication, it is difficult to separate the two concepts because people would always ask: How can this biogas be produced? Is there enough CO_2? Moreover, what is the source of the biomass?

Some experts from industry considered that there are niches in which people are willing to pay for more expensive bioproduct; however, stakeholders from industry also indicated that for this concept to work, the price difference between a conventional and a biomethane based product should be at an acceptable range.

Besides, stakeholders from industry contemplated it is essential that people be sensitized towards the products and services that are being offered with biogas and PtG. They expressed that people would be ready to pay for a feeling that they are doing something good for the planet.

Following this matter, various stakeholders from industry specified that they do not know how this environmental awareness could be achieved in society, because ultimately, for many people the most critical issue is the price of the item. Contributors from industry understand that once the biomethane derived services and products have the same price as fossil-based ones, people would be willing to buy them.

However, various experts from industry accentuated that there is a point in which the market demands some intervention from politicians, in order to remain profitable. Participants from industry showed the conviction that the extension of bioenergy projects like biogas, which demand land for energy generation, also depends on the political will, but ultimately on the opinion of the public.

Nevertheless, when discussing this matter, stakeholders from industry believe that politicians are afraid of supporting biogas because they fear that their popularity could reduce if they promote the biogas technology.

Stakeholders from politics

In their part, various participants from politics expressed to be convinced that people will accept the PtG technology once they know about its benefits. Some stakeholders from politics considered that people would understand the role of biogas and PtG, using excess renewable electricity and CO_2 for additional biomethane production. They also expect that people will not be skeptical about these technologies.

Interviewed stakeholders from politics believe that if some of the criticized issues in biogas are solved, then, people would accept the technology and its innovation with PtG. The impression of some participants from politics is that currently, this criticism is less present in society. They expressed that the contrary opinion about biogas as the result of institutions such as the German Energy Agency (DENA), the ministries of environment and agriculture, which have dedicated funds to promote proper management in farms connected to the biogas production. Nevertheless, there were participants from politics who believed that biogas and the bioenergy sector, in general, have developed and continue to have a very negative image in German society.

On this matter, various stakeholders from politics considered that people would not necessarily differentiate the use of biomethane as an alternative for natural gas or fossil-derived raw material and its associated climate benefit. As one interviewee from politics said:

"The criticism of the traditional biogas production is currently still present because people know that there are deficits in the state of the art of biogas facilities. Due to the speed of construction, many of them are not yet on the [safety] state they should be today."

Furthermore, stakeholders from politics expressed that they believe biogas was criticized because of the extensive maize monoculture and most importantly, because of the costs involved in its production. Besides, participants from politics indicated that biogas is still one of the most expensive renewable technologies.

Due to this fact, participants from politics considered that the discussion on biogas could continue as a result of the wrong development in the biogas sector. Interviewees from politics explained that because of that undesired progress of the biogas industry in the past, there could still be some distrust in the population about the technology and its innovations.

Regarding people's acceptance, stakeholders from politics stressed that the society would welcome the reduction in the use of energy plants for biogas or the processing of its derived products in the industry. Moreover, they pointed out that there are still negative headlines about the production of biogas. Participants from politics elucidated that this negative perception in people needs to be removed if one wants to implement and obtain support for PtG. In this line, participants from politics understand that the media should inform not only about the negative cases (safety risks of biogas) but also, about the positive ones (chances or opportunities) in biogas and PtG. If this is not done, then one loses the possibilities embedded in both technologies, they add.

Another topic raised by participants from politics is that even when people in Germany are ecologically aware in comparison to many other countries, consumers are not willing to pay the price of renewable energies. These participants argued that people only want to consume what is cheap for them.

On this matter, some participants from politics highlighted the following:

"The willingness to pay for renewable energies is very low because they are too expensive; it costs money and people want something that is best for their pockets."

Stakeholders from associations

Among stakeholders from associations, there was a perception that people are not entirely aware of the concept of climate change and the need for technologies like biogas and PtG that help reduce GHG emissions. They considered that these technologies are complex topics and regularly, ordinary people either do not grasp the technical concepts presented, or research institutions do not present their works in a way that a broad public can understand them. In this regard, participants from associations indicated that if biogas and PtG are not well understood, people will only think of their economic benefits and not on any environmental service.

For example, one interviewee from associations said:

"I am not certain if the German society is aware of what the concept of the energy transition involves; for example, regarding climate change. I think they are not aware of what this notion means. So, if they do not consider its effects, then, what would people notice first? - The effects on their pockets. Therefore, I think it is not enough to tell the public: okay, with this technology [of PtG] we can stop climate change [...]"

There were some participants from associations, who indicated that the perception of biogas in society is now neutral if there are no genetically engineered archaea in the fermentation tanks. Those stakeholders from associations believing so suggested that if genetically engineered microorganisms are used, there could be points of conflict with specific groups, which could generate a negative discourse against biogas.

However, these participants from associations indicated that it is difficult to foresee such a response. Conversely, other stakeholders from associations considered that the population still negatively sees biogas, especially if they see people simplifying their assessments and express: "because of renewable energies my electricity price increases."

Being aware of these possible perceptions in society and avoiding any misconception in the population about biogas that could limit the growth of the sector, some stakeholders from associations mentioned that it is essential to inform and integrate the population on any biogas and PtG project from the very beginning. This way, they said, any rejection or criticism from the society is avoided. Some stakeholders from associations mentioned cases in which biogas projects were readily accepted and even when accidents occurred; however, because people were informed early enough about the biogas installations, community's responses were not radical, and a solution could be found. Talking about this issue, an interviewee from associations said:

"I think people do not like it if you do not inform them [about any biogas project]. and maybe take them as stupid when expressing – okay, in any case, you do not know what it is going on [in a biogas plant]. That is why I would rather suggest informing [especially, impacted communities] from the beginning about what exactly it is being done there and let them know about the embedded benefits if there is any."

Experts from associations considered that people criticized a lot the use of maize in biogas and because of that, now the biogas sector has a contrary position in people's minds. Stakeholders from associations believe that the criticism towards the sector was substantiated because there were many problems associated with biogas. These participants described that in the process of the biogas expansion, there were many mistakes done, e.g., the conversion of grassland into agricultural land.

Moreover, participants from associations expressed that such expansion was controlled in areas where there was political interest to do so, but in others, this expansion was not steered, which led to pressing problems. Related to this matter, some stakeholders from associations understand that the society is not very tolerant regarding wrong techniques and externalities from biogas and agriculture and this aspect need to be considered in the introduction of innovation in the biogas sector.

Stakeholders from associations, therefore, see it is necessary to explain to people how agriculture and biomass production functions, for example, that the producer needs a certain amount of land and the whole process involves costs. Then, one must ask people what they value the most and how much they would be willing to pay for it.

As one interviewee from associations put it: *"There is a fierce distance between the population's ideas of agriculture [and the way biomass is produced] and how it works. It is thus crucial to provide information on how agriculture works."*

Several stakeholders from associations considered that the change in the political support for biogas was driven by people's criticism of the technology, especially because of the extensive maize monoculture in agriculture for biogas production and an undifferentiated "Teller-Tank" debate. They expressed that this generalization in the biogas sector led to dramatic changes in the way biogas was being supported, which resulted in an uncertain future for the field. Moreover, several stakeholders from associations considered that biogas had been picked out as a negative central theme in the news, only when accidents were happening in some plants. They expressed that this news was then generalized as if accidents were happening in the whole biogas sector. On this issue, some stakeholders from associations expect that the discussion on increased land renting prices will continue if biogas continues to depend on energy plants.

5.6 Political conditions

Stakeholders from science

Overall, stakeholders from science agree that the biogas sector is under pressure because public support is missing. By that, stakeholders from science mean that the interest of politicians to endorse the biogas industry is lacking. Because of that, these participants believe that there will be fewer biogas plants running in the future; nevertheless, there were some experts from science who expect politicians to continue supporting biogas and the biomethane production.

Regarding governmental support, some participants from science see recent changes in the kind of incentives in the bioenergy sector as a danger in biogas investments. Experts from science affirmed that PtG is an emerging technology that needs incentives to be implemented and they believe that even when there are funds for research projects and pilot plants that would not be enough to introduce PtG in the biogas sector. Talking about this issue an interviewee from science indicated:

"New technologies, like PtG in biogas, need financial support at the beginning because you will have first novel plants. There will be some support like research funding for these pilot plants, but I think this is still not enough to have a significant market effect as we saw with solar power, which showed a solid decrease in costs. You would have that [reduction in costs] only if you have a market for the technology if you have many plants and that is a big challenge. There is no political support or willingness of giving such type of financial support anymore [in the biogas industry]."

Also, for some stakeholders from science, the support of biogas is not so simple as just about subsidies. They indicated that such political interventions should not be a gift from the population; participants from science expressed that biogas and PtG should be framed as service providers, for which people pay.

Referring to this issue an interviewee from science said:

"[…] For me it is not that simple: you take this here and subside there. I do not like the word subsidy very much because it always gives the impression as if this is a donation by the taxpayer."

Some participants from science indicated that if there were security measures established, which could assure investments in the sector, e.g., through laws and regulations, shareholders could get interested in the biogas technology. According to some interviewed scientists, such approaches could ease the introduction of the PtG technology in biogas. An alternative mentioned by stakeholders from science in the absence of political intervention is the development of carbon certificates.

Nevertheless, several participants from science rejected this latter idea, expressing that technically, there is no CO_2 market for biogas producers. Despite their use, this mechanism is only available over the EU emissions trade system and such a scheme is solely feasible for upscaled biogas producers, not for farmers. In that sense, the climate protection potential of biogas is currently not exploited, indicated several participants from science.

In general, stakeholders from this sector agree that political and investment challenges are the most important ones in the adoption of PtG in biogas. They expressed that the EEG should be based on a long-term perspective and with a goal in mind, considering the potential of technologies for energy storage. Participants from science emphasized that sociopolitical challenges and the energy cost-benefit balance are essential aspects to review in the implementation of the PtG technology. However, several participants from science believe that more relevant would be to state that nowadays the real problem is that the need for a flexible power market is still shallow.

Many of the interviewed participants from science agreed that without subsidies, there is no stimulating business model for the biogas sector. They believe that currently, there is an unbalanced political framework, which brings many uncertainties for biogas producers, especially for farmers. Nevertheless, many of them seem to be optimistic about the farmers' future in biogas. Talking about this matter, an interviewee from science said:

"It [biogas] is a risky investment because when they [politicians] change every two to three years the regulations, farmers cannot rely on them. The main issue in politics is to be stable and consistent and politicians should not change regulations so constantly."

Some participants from science have the opinion that there are politicians who fear to get involved with biogas, due to the land use problematic. Thus, biogas would be a difficult topic to bring forward. As an interviewee from sciences said:

"I believe that some politicians are worried that electricity bills will become too high for renewable energies, besides, bioenergy will make the food too scarce and expensive. These are aspects that need to be considered within the [biogas] field."

Another issue highlighted by some of the stakeholders from science was that there are opposing interests from the government in the energy policy. They expressed that it is easy for politicians to substitute the input biomass with biowaste and residues in their regulations; but it is difficult to do so in reality because of the low energy content in these substrates and the challenging cost-benefit relationship in this substitution. Participants from science expressed that there is currently a dilemma in politics: on the one hand, there is interest in expanding and increasing the yield of renewable energy sources, including bioenergy; but at the same time, there is an interest in finding technologies with reduced costs, low environmental footprint, lessened demand on land and reduced associated GHG emissions.

Regarding the continuous changes in the EEG, some stakeholders in science believe that it happened because of the influence of lobby groups. These stakeholders added that seeing the variations in the energy policy in the past, they understand how weak the biogas sector is, with much less influence as a lobby sector and, in which its interest groups do not always work together.

Talking about this issue, a participant from science indicated: *"I think that conventional companies have a historical linkage with politicians, while new sectors [like biogas] do not have this kind of relationship with politicians."* Moreover, experts from science expressed that specific groups polarize the public opinion, showing selective negative information about biogas in the media. Contrasting to these ideas, some participants believe that the changes in the EEG were done to correct previous wrongdoings happening in biogas installations throughout Germany.

Stakeholders from industry

Within this sector, participants agree on the argumentation that so far, there has been an erratic energy policy in Germany, promoting first the production of biogas and later, limiting its expansion. First, they said, there was an interest in energy generation and now, it is all about climate protection. Stakeholders from industry expressed that the changes in energy policies have been done randomly and not managed as a future-oriented and lasting strategy.

As one interviewee from industry puts it:

"The main problem is that we did not have a long-term [energy policy] concept in Germany. The government put out this EEG 2004 and then, as we saw, they started to change completely and stop the conditions every three years; thus, there was no strategy behind it."

These constant changes in the energy policy, as explained by several experts from this sector, generated insecurity in investors and producers, constraining the continuity of further investment in the biogas industry. Additionally, these continuous changes generated distrust in politics and politicians, since they, politicians, see themselves unable to plan in a long-run, as explained by some participants from industry. Moreover, interviewed experts from this sector highlighted, that if the biogas technology remains being expensive and the political interest is not available to support the PtG technology, it will not be easy to continue in the field or to implement this PtG innovation in the biogas industry.

In the opinion of several stakeholders from the industry, the primary challenge of the biogas technology is the current purchasing costs of electricity and the additional costs through the EEG. Participants from industry understand that due to current regulatory framework conditions in the energy sector, the biogas technology is economically not supported to continue in the market. Now, they say, biogas is not seen as an energy storage concept, but as an energy supplier. Additionally, experts from industry explained that biogas producers are paying taxes twice, both as a producer and a consumer of energy, which in their eyes is not favorable for biogas producers.

For some stakeholders from industry, the constant subsidies to biogas in the past generated such a discredit in the population that they, stakeholders from industry, would prefer to avoid those subsidies when talking about implementing PtG in biogas. Various participants from industry prefer that the PtG technology enter the market on its own, without any governmental support. When talking about this issue, a stakeholder from industry indicated:

"There is in my view such a bitter aftertaste when you always promote something that may eventually become economically feasible. I would rather make money for the area PtG so that we need no promotion or incentive to insert it into the market."

Some stakeholders from industry believe that in Germany there is no business anymore for biomethane, due to the existence of for them unfavorable energy rules given by the government. Because of this situation, some stakeholders from industry are considering pivoting to other European countries, where people are more keen to pay for a premium or green methane. On this matter, several participants from industry considered that in the beginning, the EEG legislation was a model for many other countries; however, Germany has lost its goal from what was the interest 12 years ago. As an interviewee from industry put it:

"In Germany, there is no market anymore for biomethane, especially in the field we are working in this industrial scale. There is no way to work with biomethane with the new rules the government gives us. The main problem we see is that there is no real strategy behind it, what the government is doing with the renewable energy. With the EEG what was a role model for many countries, which [simply] copy-pasted it, but then, Germany lost the way they started 12 years ago."

Some stakeholders from industry criticized the interest of the government to set climate protection goals, without setting any business mechanism to achieve them. They expressed that if biogas is "discriminated", it will remain to be one of the most expensive renewable energy sources. CO_2 certificates were mentioned by some stakeholders from industry, who indicated that this could be an interesting approach. However, other participants from industry emphasized that this mechanism has proofed to be inefficient since the price is too low for biogas producers.

In general, stakeholders from industry agree that biogas could help achieve the German climate goals; the question they posed as if it is flexible enough to provide energy when it is demanded. As a participant from industry phrased it:

"We have the question: what do we promise to ourselves? We have CO_2 mitigation targets: how can we achieve them? If we use biomethane compared to natural methane, we generate 80% less CO_2 emissions. If this is important for us, then, we must create the incentives and conditions to support such technologies. Alternatively, conversely, we can make CO_2 emissions expensive again. Otherwise, we will not reach the climate goals."

They believe that if the political interest is to reduce GHG emissions, financial instruments should be made available to investors. Otherwise, those aims would remain just a vision or an ideology from politicians. Several participants from industry believe that what has been observed with the changes of the EEG, it is an adjustment of the energy regulation based on the generalized public opinion, rather than the other way around, or any potential influence of lobby groups, as expressed by other stakeholders. However, there were also participants from industry who indicated that politicians are instead those who influence the public opinion and not the way around.

Regarding how the public forms its opinion, some participants from industry expressed that this is mostly influenced by lobby-work of large companies, while the bioenergy sector is instead organized in small lobby groups. Moreover, some participants from industry expressed their concern about the risk of leaving the biogas production to large companies, which control energy production and distribution. They argued that when farmers produce biogas, the energy supply is democratized; since its citizens produce it. This situation is then different from when large foreign companies provides the bioenergy.

Moreover, an additional challenge some stakeholders from industry reigned the opinion that people do not understand the relevance of biogas, e.g., that it helps generate an autonomous energy supply and reduce GHG. They indicated that if the role of biogas is not understood, people will only focus on the energy price.

Stakeholders from politics

Like previous participants, stakeholders from politics believe that for PtG to succeed as an innovation in biogas, political support is essential. Several of the participants from politics indicated that without this governmental support, it would be difficult to adopt and expand the PtG technology, mainly due to economic reasons.

Several participants from politics argued that since political measures have a considerable influence on the renewable energy sector and especially on biogas, this is an element that will influence the most the further development of this innovation in biogas. As one interviewee from politics said:

"If politics does not intervene, for economic reasons, relatively little will happen. It just will not be feasible to implement. That means it [PtG] will remain in the field of pilot plants."

Regarding the reasons for changes in the EEG, some stakeholders from politics considered that an essential factor for its changes was the influence of lobby groups from other renewables, e.g., solar energy and companies from natural gas. Several stakeholders from politics believe that politicians followed lobby groups and did not create the needed regulations for the biogas sector, a situation that could continue to happen in the future.

Quite the opposite, there are stakeholders from politics who reject this argumentation and expressed that these changes in subventions and the conditions for the biogas sector have little to do with lobby work, but this was as an alternative a process that occurred spontaneously. Other participants from politics expressed that the change in politics was due to the influence of people's attitudes in political decision making since there was discontent among the population due to the high energy prices. As one interviewee from politics put it:

"The reason for the reduction of political support is not clear to me. It could have been because of the social pressure. I think that the critical landscape and the social pressure influenced by the high cost of the EEG led to the situation."

Overall stakeholders from politics believe that after the 20-year contracts expire, it will be difficult for biogas producers to remain in the market based on energy plants. They must define how to remain operating and be competitive with their business models.

Some participants from politics considered very problematic the fact that technological know-how and possibilities for further development in biogas are being destroyed, in their eyes, due to current policies in Germany. Several stakeholders from politics criticized the tendering model of the EEG amendment in 2017.

Stakeholders from politics understand that possibilities for growth are minimal under that concept. Also, some of these stakeholders consider that the tendering approach is an inappropriate instrument because it does not allow the participation of different actors in the energy supply from biogas, especially for small producers.

Stakeholders from politics expressed that small producers cannot take part because they do not have the conditions to get into that system, due to the high requirements to elaborate a proposal and deal with the process for approval.

For example, one interviewee from politics said:

"Tenders are just the wrong instruments because they do not encourage a variety of actors to participate, especially not the minor and decentralized ones. These actors cannot participate in tenders since they do not have the potential to fulfill the high requirements for an application of such market systems."

Participants from politics added that in this tendering system, only large companies could take part, which does not have any interest in decentralizes energy production, or in questions regarding environmental protection. Therefore, currently, the energy legislation is inclined to support only one side and one group stressed some stakeholders from politics.

Another challenge mentioned by various participants from politics was the amount of excess electricity that is generated, which should be synchronized with the number of working hours in a PtG/biogas plant. Stakeholders from politics agreed that at this moment a political task ahead is to integrate biogas within the portfolio of various renewable energies available in Germany. They believe that now, the attitude in the political sector is not ideal, which generates much uncertainty at a local level. Because of that, some participants from politics have gained interest to come up with their plans and ideas to a European level.

As explained by a stakeholder from politics:

"Unfortunately, currently there is no support for biogas from the Union or the SPD. That worries me very much, so of course, we must push the development of biogas on the EU level too."

Various stakeholders from politics suggested going to a European level to free farmers' associations generating energy in a tendering system. In this way, they explained, chances are open for these associations to produce energy in a decentral way, receiving incentives for its storage capacity at a European level. Those participants from politics believe that if this would be the case, many regional projects could flourish. Nevertheless, they coincided that the development of a framework condition for biogas is purely in the hands of the consumers, or in other words, a decision of the voters. As one interviewee from politics put it: *"The existence of any framework condition, or sales possibilities to achieve profits in biogas, is naturally always the decision of the society."*

Stakeholders from associations

Some interviewed experts from associations showed conviction that politicians follow people's attitudes, changing their support to the biogas sector given strong discontent in society towards biogas. Conversely, there were also participants from associations, who believe that politicians are instead of systematically blocking the development of biogas. Those stakeholders think that politicians have stigmatized the technology, transferring their views to people. Interviewees from associations considered this attitude of politicians as unfair treatment, ignoring the impact of other sectors on the environment and focusing only on the biogas industry. The comment below for a stakeholder from associations exemplifies these opinions:

"Politicians unilaterally focus their criticism on bioenergy as a whole, but for example, they do not take other aspects such as intensive animal husbandry into consideration."

Some participants from associations believe that in the last years, policies have been strongly influenced by lobby groups, changing the support towards biogas. Experts from associations expressed that large companies, with much money, have persuaded politicians for a long time, having more influential participation in lobby-work than that of the biogas sector.

Thus, participants from associations argued that the introduction of any technological innovation does not depend necessarily on what people want or need, but on the interest of some industrial groups. Several stakeholders from associations affirmed that the perception of biogas in public was influenced by several groups, including those from animal husbandry, farmer's associations and the food industry, which all compete with biogas production. Participants from associations expressed that those groups developed campaigns against the bioenergy sector.

Nevertheless, there were stakeholders from associations believing that those changes in the EEG policy, varying the support to biogas, was due to the negative public opinion towards the sector and not because of any lobby group. However, some participants from associations responded that if it had been the response of any community, the reason for the change in the energy policy, regional/local politicians would have been the first interested in making a change or lobbying for it, which for some was not the case; they perceived that the changes came from above.

As one interviewee from associations said:

"I can well imagine that if a deputy in his constituency faces much criticism, where people complain about him, for example with statement like: "there are many maize monocultures, biogas stinks and so on...", then the deputy would be personally very interested to solve the situation and even put money on the issue. However, I do not think that it is just a single deputy, who influenced the whole energy policy in the country. I do not think so. I think other players were involved in this situation."

Some of the stakeholders from associations affirmed that biogas also exerted some lobby in the political landscape. However, because of being a small sector, its network is more limited and less structured in comparison to other influencers.

Furthermore, several stakeholders from associations expressed that due to the lack of coordination among the different bioenergy players, their lobby work was not as practical as other sectors, which are more massive and better organized. On this matter, a stakeholder from associations indicated: *"The biogas area may be too new. It has been developed only in the last ten years. I think its actors did not have the time, nor the people, [nor money] to build up any network in Berlin."*

Moreover, some participants from associations believe that the reason why the needed political support will continue is that those who endorsed the biogas industry are no longer in the political arena. These stakeholders also expressed that now other topics are being discussed in the parliament, e.g., refugees or costs in the energy sector, which has been put ahead from the biogas and the bioenergy sector in general. Nevertheless, participants from associations agree that if PtG reaches to be well positioned in public, then, politicians could make use of it as a means of prestige to get the sympathy of many people.

"We have seen that some new technologies, which promise some potential and perspective into the future, are being used as objects of a campaign by politicians. I believe this approach has no disadvantage or no negative consequences."

According to some stakeholders from associations, what is needed in biogas is a reliable framework condition to cease changing the energy regulation so frequently. Otherwise, a stakeholder from associations advice that investors will feel their money is at risk and subsequently, could shift to other, more secure sectors.

5.7 Technological barriers

Stakeholders form science

Some participants from this sector expressed that PtG could transform the biogas value chain, about the type of stakeholders and their synergies handling the technology. They stated that highly knowledgeable operators could displace some biogas producers (especially farm-based plants). On this subject, various stakeholders from science argued that they foresaw this innovation to be adopted primarily by large plants and suggested the closure of small biogas production sites. For example, one interviewee said:

"I think that PtG will be more feasible for bigger biogas installations. Maybe it also leads to a shift, closing small plants and focusing on bigger ones."

In contrast, as the comment below indicates, other stakeholders from science stated that farmers who already operate biogas plants, possess the skills to manage a PtG installation.

"I can imagine that such electrolysis is operated directly by the farmer [a biogas plant operator]. If they can operate a biogas fermenter and combined heat and power plant, with a processing technology; then, they are also able to operate an electrolysis unit. I see no problem with this issue."

Concerning the competitiveness of PtG versus other methane upgrading methods, some experts from science perceived PtG as competing to existing techniques, while other stakeholders from science consider it solely as a complementary technology. Another aspect these stakeholders highlighted is the contention represented by similar storage technologies to PtG, such as batteries. In this aspect, some said that the selection of any technology beyond its technical and economic feasibility, it is a political question.

As to energy efficiency, it was evident the skepticism among the stakeholders from science towards PtG. In general, these participants were inclined to avoid long transformation chains of renewable energy into other products, e.g., electricity to biomethane.

Experts from science justified that along the conversion pathways, there is an energy loss and thus, the process becomes less efficient. Because of this reason, some participants from science were suggesting using H_2 directly, or use the electricity for transportation.

However, there were interviewees from science who defended PtG versus batteries; to their opinion, PtG could be less cost-intensive and is compatible with the already methanation concept in biogas. Talking about this issue, an interviewee said:

"Compared to, for example, storage batteries, I think it [PtG] has the chance to be cheaper than batteries and it is more feasible because we have the biogas reactors already out there. I think there are not so many batteries available right now. They would be built and developed first."

Another aspect highlighted among the participants from science was the scalability of the PtG technology. They expressed their concerns about bringing the technology to the market, away from pilot projects. On this point, some of the participants showed optimism about the technical performance of PtG. However, some of them indicated that there are still procedural parameters that need to be further investigated (cf. 5.11).

Lastly, the stakeholders from science emphasized the constraint that electrolyzers cannot work continuously in a biomethane plant. They highlighted that there is a CO_2 coefficient in PtG, meaning that it is expected to double the methane generation in the best case, without needing to increase the amount of biomass and in this way, exhaust CO_2 can be reused. Nevertheless, they indicated that this effect could only be seen in some seasons since the electrolyzers work for only 10-15% of the annual hours, equal to around 10-20% CO_2 emissions avoidance.

Stakeholders from industry

Similar to the previous participants, stakeholders from industry punctuated the idea that PtG would be a technology managed by specialized companies. In this regard, they foresee farmers to be suppliers of raw biogas and CO_2, as part of a kind of cooperation between different actors in the biogas value chain. These stakeholders justified their opinions, by stating that large companies have technicians available and much more trained personnel in comparison to traditional farm-based biogas plants. As one interviewee said:

"I suspect the role of actors [in PtG] will be similar to the current biomethane [production]. Since farmers care mainly for their raw biogas, the treatment is very often done in conjunction or cooperation with energy suppliers. This raw biogas is usually outsourced. Either via the manufacturer or a special provider."

Moreover, participants from industry criticized the need to have an additional conversion stage from hydrogen to methane. In this aspect, they showed much confidence in scientists to provide them with reliable information about which pathway is more meaningful. Another aspect mentioned by these stakeholders was the topic in relation to competition for PtG in biogas. They indicated that they do not see any competing technology except the traditional upgrading facilities. However, with those technologies, they said it is not possible to have a flexible energy generation.

About batteries, stakeholders from industry pointed that they are not competing to PtG because they need to be charged regularly; hence, they do not offer much flexibility like PtG. When asked about the catalytical conversion, they indicated that in general, gases from biogas are not very compatible with this technology. They explained that to make possible the use of catalytical methanation, gases obtained from biogas would need to be purified, e.g., by absorption. Overall, they did not see catalytical methanation as more fitting for biogas plants and especially not for the flexibility concept. The following is an extract of a comment on this matter:

"There is the chemical methanation, which can also transform CO_2 and H_2 into CH_4. However, the gas used needs high purity. There, a nickel catalyst is used, which reacts very sensitively to gases. That is why we and others believe that it is not the right choice for this application in biogas, where there is a mixture of gases."

In the end, stakeholders from industry emphasized that PtG can be of relevance if it could be implemented in currently existing biogas installations, without the need to build new plants. An additional challenge mentioned by the stakeholders from industry was that in their view PtG is still very complex and costly. As a result, they suggested that the technology should be developed to be less expensive. They demanded several characteristics from PtG, e.g., to be stable and easy to handle and meant that there are still aspects that need to be demonstrated in the technology.

Stakeholders from politics

An aspect that was stressed by these stakeholders was the challenge confronted by biogas installations to become flexible. Since there is a pressing demand to make the energy sector adaptable to market conditions, stakeholders from politics believe that many biogas plants will be modified, or as commonly referred "re-powered".

In light of this, participants from politics showed uncertainty about the level of flexibility that biogas plants could achieve. They specified that in summer when there is an exceptionally high amount of excess renewable energy, there would be a demand to store it. However, stakeholders from politics wonder how it could be assured that the installed capacity of biogas plants can be augmented without increasing the number of biogas plants.

They indicated that seasonal variations are currently a challenge for the biogas sector because the installations cannot be adjusted now with the current technological set-up. For this situation, they envisioned two options: i) to store the biogas in the form of biomethane as proposed with PtG, or ii) adjust the feeding frequency in fermenters. Another challenging aspect stakeholder from politics mentioned is the increasing criticism of using biogas as the preferred mechanism to treat manure. They communicated that some interest groups are suggesting other options, such as covered storage tanks for homogenizing the manure. This choice, they expressed, is well-known and is significantly cheaper than installing a biogas plant, which would become more expensive with an electrolysis rector. Participants from politics perceive alternative and cheaper technologies to be a technological challenge for the biogas sector, which needs to be tackled. However, they acknowledged that with the tank approach methane would not be gained, representing then an opportunity cost.

Among the stakeholder from politics was common the opinion that PtG does not represent any change in the operation of a biogas plant and also, it does not demand any transformation in the type of substrate to be implemented. They alleged that through the implementation of PtG in biogas units, the biogas value chain would not be significantly transformed, especially in the kind of feedstock or input material.

Interviewed stakeholders from politics conveyed that PtG represents a significant improvement in the biogas conversion efficiency, reaching methane levels of up to 90-95%. However, they indicated that biogas plants should provide a reliable source of energy, for which there should be sufficient and sustainable input sources, either from maize, biowaste, sewage gas, or any other.

This aspect is still an issue that should be clarified with this technological concept. Concerning actors handling the innovation, experts from politics perceive PtG as a quite complex technology, which cannot be operated by a farmer. They expressed that farmers are not trained in process engineering.

Thus, they are not the appropriate actors to run such a PtG technology. The following extract exemplified the opinion of participants of politics on this issue: *"I can hardly judge now if the farmers are the right operators, but if you see what problems there are in biogas plants, I have serious doubts. The question is whether they even get permission for running such [complex biogas] plants."*

Stakeholders from associations

One aspect that was highlighted by these stakeholders was the accessibility and availability of the input material (how far it is and how much there is). Participants from associations considered that without a safe supply of the substrate, the PtG technology could not prosper in biogas. They indicated that by installing PtG, the input material would not necessarily change. Stakeholders from associations also expressed their concern that people could criticize them if they support the use of this technology and do not contrast its efficiency with another one, like catalytical methanation or the direct use of excess energy.

Moreover, they indicated that there could be some opposition if there is a need to build new plants or gas lines. As a participant described: *"I do not want to incline towards any technology and say: I would like to build a hydrogen network. I see that from a social point of view, there will be strong opposition. In other words, it is elegant to use the existing natural gas infrastructure."*

Furthermore, stakeholders from associations seem not to be certain about the type of biogas installations that would fit best to PtG and under which costs. Another aspect that was unclear for them was the type of consequences that could emerge from PtG, especially, the type of emissions, what is the recycling potential and the demand of special construction material that could influence its environmental footprint.

Similar to previous stakeholders, interviewees from associations accentuated that through PtG there are different energy losses in the transformation pathway from electricity to biomethane. There was no agreement among the participants regarding what is advisable to either use H_2 directly, store it in its gaseous form, or convert it into methane. They also mentioned that other concepts could emerge and compete with PtG.

As a stakeholder from association stated: *"Of course, it is possible that other techniques can be developed, which could be as efficient as PtG and could be convenient storage options. That would, of course, be a risk for PtG. That we will see."*

Consequently, stakeholders from associations mentioned were the response time of the microorganisms as an additional technological challenge, if they must be adapted to flexible feeding times. They indicated that some microorganisms could become inactive in the methanation reactors and ultimately that could slow the conversion process down.

Other technical aspects that were briefly pointed by the stakeholders from associations were: the volatility of H_2, necessary for safety issues and the technical challenges to upscale the theoretical concepts of PtG.

5.8 Economic constraints

Stakeholders from science

Participants from science mainly pinpointed that despite the low willingness of consumers to pay more to have environmentally friendly products, nowadays, many companies get interested in implementing concepts of a "circular economy", closing loops in their systems. Stakeholders from science warned that if energy costs are too high for consumers, a PtG concept greening the biogas sector could potentially fail.

About the input substrate, some interviewees from science explained that an energy storage concept with biogas could not become competitive in comparison to other technologies if the model remains to be based on maize as feedstock. Some stakeholders suggested considering Miscanthus as a substitute for current energy plants since it is cheaper to produce and has fewer cultivation demands. These participants argued that once biogas plants get out of the EEG tariffs, there will be a financial challenge regarding the biomass source, which is one of the most significant cost factors in the biogas value chain. Stakeholders from science emphasized the challenge for the biogas industry to find cost-effective substrates to make the energy production profitable.

A further topic discussed among stakeholders from sciences was concerning the attractiveness of the biogas technology in contrast to other sectors demanding H_2. The interviewees from science indicated that only those sectors that have lower production costs would be able to survive in the energy market.

The stakeholders from science believe that those bio-refineries, with many years of experience and with highly trained personnel will be much more competitive than many biogas producers loaded with increased costs.

Experts from science also emphasized the costs involved in building hydrogen infrastructures (electrolyzers), which they specified are considerably high. They believe that the most significant barrier in the PtG technology will be the investment costs. On this detail, participants from science understand that there will not be sufficient funding available for this technological approach.

Talking about this issue, an interviewee from science said:

"I believe that the main challenge is to become an economy of scale: the bigger the plant, the cheaper the specific investment costs are. Contrarily, we have the challenge of availability of substrates in a certain location, because you must mobilize it. If this transportation is occurring from long distances, it [the production] then gets expensive. This [situation] is always the challenge with regards to biogas projects. In the case that you have large amounts of biowaste and manure available, this is then the best solution [if it is overall cheaper]."

Finally, participants from science discussed the potential of developing the PtG technology and sell it to other countries, expanding the target markets. Nevertheless, interviewed stakeholders from science asserted that this process might have complications. They explained that in countries like France it would result challenging to introduce the technology because there, people like having their concepts. This situation is apart from the competition with other and less costly energy storage concepts that may be abundant in the market.

Stakeholders from industry

Some stakeholders from industry expressed that in their companies they analyzed the PtG technology, but because of financial reasons they preferred to explore other markets rather sell their traditional biogas concepts. Moreover, stakeholders from industry stated that PtG means a return on investment within 15 years to them, which they deem to be a too long period.

Participants from industry indicated that while inspecting the possibilities of PtG within their teams, they found no retail concept that could be implemented into their business models. They emphasized that the current political context not benefit the economic feasibility of the PtG technology, from more than just doing experiments. As one interviewee put it:

"As far as I know, there is no real potential to store this excess [renewable] energy. This PtG [concept] could be a way for that, like some others, but it is so expensive that you cannot even think about it more than to make research and development."

Another economic aspect participant from industry reiterated was about the feasibility of any biogas project having biowaste and manure as their primary substrates. Some stakeholders within this sector indicated that their business models could only run if they keep using energy plants. They made clear that there may be a possibility somewhere to change the input material, whenever there are large quantities of manure and biowaste; but according to their investigations, in Germany they do not see any possibility for that under current rules.

Stakeholders from industry marked up that from their market research; there is not enough waste available in a reasonable range that could be used professionally or commercially. They added that biowaste could be used as one of the substrate mixes, but not as a primary biomass source.

Furthermore, several stakeholders from industry expressed their concern about the existing energy directive, the EEG; declaring that it does not provide any economic incentive to invest in the PtG technology for BM. That issue is for some stakeholders from the industry of vast disappointment.

It was evident to see a keen interest in this innovation in biogas among participants from industry and their eagerness to create synergies among multiple fields to build a market. However, they indicated that political conditions are considered not supportive of any business model with the PtG technology.

Stakeholders from politics

Similar to previous participants, stakeholders from politics mentioned that PtG as part of biogas faces intense competition with substrates (biowaste and manure); against multiple other uses, e.g., municipal disposal centers that also demand this type of input material. Also, some of the stakeholders from politics indicated that due to the high water content and the relatively lower energy potential of manure, it is economically less appealing to use this residue for energy production than energy plants.

An aspect that was stressed by several stakeholders from politic was that they would not be willing to promote the technology in its current stage. They indicated that because the economic feasibility of PtG is now not clear, they cannot either rely on nor support the technology. They emphasized that the viability of PtG should be demonstrated in financial terms. As one interviewee said:

"I have not seen any calculation to know how much it will cost in the end. What methane content do we get out of the biogas plant? Those are all things that we must clear up before one can even express that this would be a meaningful thing to have."

Some participants from politics stressed that they do not see any perspective about biogas producers to change their input substrate. They believe that biogas plants will continue to use energy plants, at least for the coming 10-20 years. If PtG is adopted in this period, then there would be still the common substrate in the industry, they believe.

Stakeholders from associations

Stakeholders from associations showed optimism about the implementation of PtG in the biogas value chain. Some emphasized on diversifying the biogas portfolio, by searching for several market possibilities, e.g., by selling the gas itself, another could be by selling the nutritionally-rich fluids.

It was common the opinion among the stakeholders from associations that economic support should exist only in the form of technology research & development; otherwise, they see any intervention in this market as unsustainable. They believe that the technology should become competitive by itself.

A recurrent theme in the interviews among stakeholders from associations was: who will pay for PtG and its high-priced biomethane? Some were expressing that biogas producers cannot expect the society to pay for it. They indicated that rather users of fossil-derived products should pay for the costs of renewable energies.

In relation to the relative costs of the biogas plants, some stakeholders from associations emphasized that those, which may want to run a PtG concept, could ultimately be more expensive; firstly because of the size of the installation and secondly, because of the relatively lower energy content of the input material. Nevertheless, they insisted on urging biogas operators to shift towards fewer energy plants, initially by combining conventional feedstock with more sustainable biomass, e.g., biowaste or manure. Talking about this issue, an interviewee said:

"I think, if someone has only manure, then the biogas process makes no sense. If you make BM, then it also does not make any sense. I think there should be a mixed substrate. So, I think you will not get away from energy crops."

Some participants from associations also highlighted that it is difficult nowadays to find new investors and producers, interested in continuing the biogas business; due besides the negative societal attitude, especially to high costs associated with PtG and the biogas production. As one interviewee put it:

"The biogas sector has a terrible reputation in society and I think this is unfair. It is difficult to find farmers or operators of biogas plants who are willing to invest their money into these biogas plants, in order to utilize other raw materials or introduce any innovation. It is also difficult to find banks to invest in a biogas plant. In the end, actors in biogas are afraid of losing [their money] and farmers also lose interest in the [biogas] technology."

5.9 Accountable actors

Figure 26 depicts the percentage frequency distribution of codes under the fourth category: “Actors to manage risks and challenges”, which emerged from the QTA (cf. 5.1, Table 5). This theme includes social actors recognized by the interviewed stakeholders, as accountable for managing risks, challenges and uncertainties of implementing the PtG concept in the biogas sector. Those actors are depicted on the horizontal axis and their frequency distribution is displayed on the vertical side, relative to the total number of interviews per each sector approached in this study. As a means of comparison, the last bar in the individual actors represents the general frequency, based on all interviews performed in this study (n=27).

Politicians were almost unanimously identified as the main actors to take charge of the risks, uncertainties and challenges discussed so far (mentioned in 26 out of 27 interviews of the investigation). Nevertheless, even when acknowledging their role in the sector, politicians still see themselves as not much accountable in this matter, in comparison to how other sectors perceive them to be. It is also relevant to notice that apart from this category, politicians were the group that mentioned the most the rest of the specified actors, with the exception of biogas producers, which were mentioned the most by stakeholders from science and associations, which was a sector that mentioned themselves as frequent as stakeholders from politics appointed them.

Stakeholders from politics understand that research institutions bear the same responsibility as they do to provide solutions to avoid or minimize risks and challenges linked to the implementation of PtG in biogas. This rank is followed by the media and associations (3 out of 5 participants), which they see equally accountable for this purpose. Participants from politics see biogas producers not much accountable to take charge of risks and challenges in biogas and the emerging technology of PtG.

Research institutions were mentioned only in 48% of the cases (13 out of 27 interviews); while stakeholders from politics mentioned scientists the most (in 4 out of 5 interviews among stakeholders from politics). Dissimilarly, stakeholders from industry mentioned scientists the least (only in 20% of the cases, in 1 out of 7 participants from industry).

As with stakeholders from politics, stakeholders from science see themselves with not much responsibility to handle risks and challenges in biogas. Only half of the stakeholders from science see themselves as responsible actors to take action in this matter; the same goes when they assess biogas producers, which were also mentioned in 5 out of 9 interviews among stakeholders from science. Scientists, in their part, perceive the media and associations as least influential in this matter.

Stakeholders from industry were practically focused on identifying politicians as the essential agents to manage the risks and uncertainties linked to this innovation in biogas. As part of the group "biogas producers" and similar to stakeholders from politics and science, stakeholders from industry see themselves with not much accountability in the topic (mentioned only in 1 out of 7 interviews among stakeholders from industry). They also lessened the relevance of other participants, e.g., scientists, associations and the media, which they even did not explicitly mention.

When asked about how they think people form their opinions and the role it could have in dealing with risks and challenges in the biogas industry, overall, the stakeholders indicated that people's mindsets are formed by the influence of political discourses, who in their part, have personal agendas and persuade people to achieve what they want. In some occasions, stakeholders from industry openly showed their distrust about research institutions and the data they provide concerning the technology in biogas. They indicated that research centers are somewhat theoretical and do not depict the reality of this innovation in biogas.

Stakeholders from associations also pointed at politicians as the executors to handle these issues; however, in contrast to the interviewees from other sectors, stakeholders from associations did consider themselves as having a pivotal role handling risks and challenges in biogas, especially about influencing people 's opinions and the attitude of politicians. They highlighted the case that the strength of the biogas sector as a lobby group is significantly small in comparison to other sectors, e.g., coal, other renewables and farmers. Moreover, they see this situation as an important reason for the continuous changes of the political panorama concerning biogas in Germany.

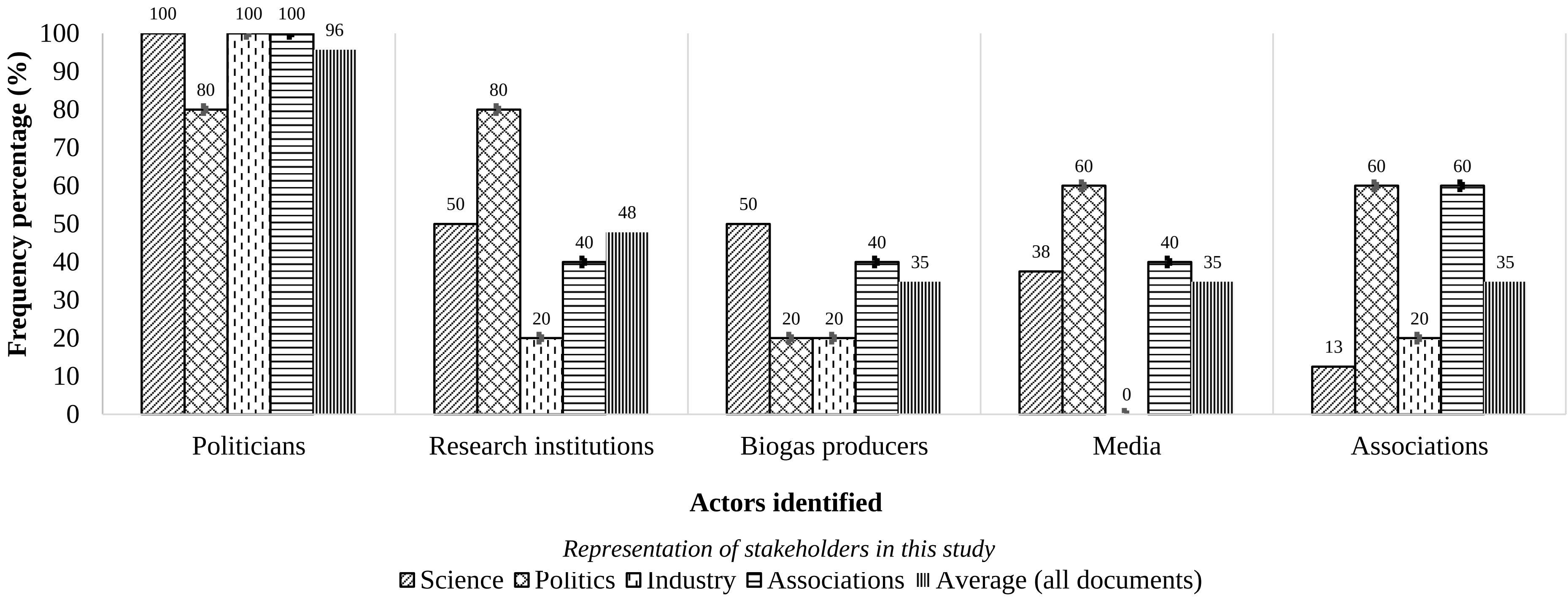

Figure 26. Percentage frequency distribution of actors to handle risks.

Stakeholders from science

Several stakeholders from science considered that biogas producers (as an industrial sector) are essential actors to manage risks of PtG in biogas, by constructing reliable plants. They argue that from an environmental point of view, producers should be responsible of both taking care of their image, but also do something with their installation, so that they do not generate many odors or that no accidents happen.

Participants from science added that biogas producers should be careful so that the criticism to biogas does not remain in society, especially about the source of CO_2. From an economic point of view, these stakeholders indicated that biogas producers are also responsible for generating their research and development programs, to analyze how they could extend their markets and generate profits in scale.

Among stakeholders from science was common the notion that science is a vital actor about the identification of “real” sources of risk and the extent to which they influence other systems. Some stakeholders consider that regarding risk assessments and management, research institutions are the main actors that should be involved.

In Accordance with the interviewed scientists, it has been demonstrated in the laboratory and small-scale projects that the PtG technology works in association with biogas; however, stakeholders of this sector believe that scientists are also responsible to upscale these projects and bring them into practice.

Finally, stakeholders from science explained that researchers should also elaborate legislative recommendations on which type of framework conditions are necessary to implement the PtG technology and how to best support it. For some stakeholders, the decisive factors about the technology of PtG are the cost of an electrolysis reactor. For that, they see science as the sector that needs to figure out alternatives on how to make this technology more economically feasible. Then, they must offer alternatives to policymakers, who then decide on ways to support it.

Stakeholders from industry

Stakeholders from industry emphasized politicians as vital actors in handling risks and challenges in biogas. They believe that politicians must carefully elaborate mechanisms to help avoid any potential accidents in connection with PtG in biogas. Participants from industry explained that a risk assessment should come from scientists, who would then advise politicians on what to do next.

Concerning the political action, stakeholders from industry mentioned that the constant changes in regulations generate uncertainty for investors and this is a challenge in the technology itself, which should be managed by politicians. They call for political attention and for a long-term vision in the energy regulation. Their perception is that politics as an institution and democratic means of governance has a vital role in deciding what has to be supported and what not.

Moreover, stakeholders from industry emphasized that PtG is a technology to be supported due to its climate protection task. They believe that unless politicians define a path for the technology, it will be difficult for it to get into the market. Hence, for stakeholders from industry, the political role is indispensable in the further development and avoidance of risks in biogas and PtG. In line with this though, some stakeholders from industry believe that if politicians decide to support local PtG-biogas initiatives, then, they could acquire more support and popularity in the people. Ultimately that could interest them because they are in search of electors.

Similar to participants from science, some stakeholders from industry consider that biogas producers are essential actors to avoid any potential accident in the plants. However, only a few stakeholders mentioned this aspect. Stakeholders from industry put weight on PtG to be easy to handle, so that farm-based biogas operators could manage them and avoid any potential risk of explosion, for example. Another aspect is about the hygienization of the digestate. In this now more elaborate setup, biogas producers should know how to handle every detail and also about the electrolyzer, to safely manage the technology.

In a different matter, some stakeholders emphasized the importance of developing a sustainable technology regarding avoidance of any potential gas explosion. For that, some identify researchers to go deeper into the topic and also politicians to define specific measures in praxis and in research.

Some stakeholders from industry indicated that rural cooperatives are essential actors for a democratization of the local biogas production. They expect that these community-based entities will take care that no environmental problems happen and will influence the prices much less than any industry in the energy market. In this regard, some call for the autonomy of the biogas production, so that the society is not dependent on what they call "Energiekonzernen" – large energy companies that are in a very dominant position, according to these stakeholders. As one interviewee from the industry said:

“From my point of view, there are many positive approaches in the communes and among the farmers who join forces to organize their decentralized energy supply, the entire energy supply is then democratized.”

Stakeholders from politics

In order to manage risks related to the implementation of PtG in biogas, several stakeholders from politics considered that the first actors to intervene should be from science. They argued that researchers should show the state of the art of a technology and demonstrate that it works and that it is safe to use. They accentuated this point to be very important that politicians rely their decisions on what scientists indicate to them. They see scientists as guides for politicians.

Among the stakeholders from politics, science (meant as natural sciences) was requested to progress in the PtG technology and this should go beyond the laboratories. It should work in reality, the accentuated. Few participants from politics mentioned the role of social sciences in terms of assessing the risks linked to a technology or potential societal problems.

Those stakeholders from politics mentioning social scientists argued that they could also provide useful ideas on what type of background is needed to make the PtG technology successful. Research institutions were perceived as similarly responsible for taking care of risks and challenges in this field and of developing the PtG technology up to a point in which it is reliable and is attractive in the market. Likewise, stakeholders from politics understand that decision-makers should analyze all the pros and cons of the technology objectively.

Talking about this issue, an interviewee from politics said:

"The industry and research institutions are responsible for developing technologies so that they are profitable and competitive. Contrarily, it is the job of politicians or legislators to make sure that a balance is made between traditional technologies and renewable ones."

Stakeholders from politics added that once the technology performance is assured, politicians should identify criteria to assess the added value of a specific technology, about the solution to a problem. Then, politicians should employ mechanisms to promote its development in its initial phases. Some stakeholders mentioned that for politicians the society is ultimately their goal number one because societies choose them to represent their interests. What the stakeholders from politics found difficult is how to influence people's opinions. On this point, they pointed that associations, the media and interest groups play an essential role.

The line of influence for people's attitudes for this stakeholder is: scientists influence politicians, indicating them what the state of the art of a technology is; the society urges politicians on what is vital for them and what do they care about and ultimately, politicians should take decisions in these aspects. Other stakeholders from politics indicated that associations and unions reach biogas producers and operators (at industrial scale) in terms of influencing their attitudes or helping them acquire measures to reduce potential risks in relation to this technology.

Stakeholders from politics mentioned that associations together with operators might play a role in increasing the acceptance of biogas and the PtG technology. On this matter, a participant from politics said: "Associations and the operator's organizations should make a common cause and accordingly, try to make a positive mood in society."

The following quote represents the attitude of the stakeholders from politics, concerning biogas managers: *"The operator is always responsible for all technical risks. He cannot get away from it."*

Stakeholders from associations

Within this sector, some stakeholders accentuated the role of producers to inform and integrate people in their projects, before anything is implemented. Stakeholders from associations indicated that the acceptance of the technology is higher if people feel that they have been considered in the planning process. In this regard, biogas producers are identified as main actors for gaining people's interest and recognition.

Some stakeholders reflected that PtG is not entirely mature to be expanded in the whole market. However, some stakeholders from associations expressed that ultimately, the science sector is the responsible one to indicate if PtG is technologically ready for its market expansion. In any case, stakeholders from associations added that PtG is a young innovation in biogas, which can at any time consider some optimization potential.

Regarding this issue, some participants from associations considered that politicians should support the PtG technology, at least in relation to research & development (R&D). This support should focus on: technological improvement, installation of demonstration plants and the initiation of projects to a pilot scale that can be further expanded up the industrial level.

Despite the importance they see in research, some stakeholders from association perceived that unfortunately, politicians listen to the advice of scientists and review the results of research institutes only in a partial way and only when their interests are not at stake. Having that condition, stakeholders from associations indicated that politicians are inaccessible because they only follow their political agendas. Stakeholders from associations added that in the last years they perceived that lobbyists have strongly influenced politicians.

For some stakeholders from associations, politicians are responsible for keeping people's interests in the first line. Moreover, they believe politicians should also be aware of the democratization of biogas plants and pay attention that large international companies do not dominate the market, leaving behind local and community-based biogas projects. Likewise, some stakeholders from associations indicated that the media is an essential element in the process of people's opinions formation, by spreading news about the technology. However, what they regretted is that in many cases the media only featured biogas when there was an accident but not when there is some good news.

5.10 Management options

Interviewed stakeholders from all sectors stated the need of policy measures as the most effective procedure to handle risks and challenges of PtG in connection with biogas; and also, as the means to compensate the benefits this innovation entrenches. Nonetheless, when asked on an ideal policy for the mentioned sector, overall the stakeholders did not provide a concrete depiction of how this political intervention should be deployed.

Figure 27 illustrates the codes' frequency distribution under the fifth category: "Risk management options & measures to deal with barriers" derived from the QTA (cf. 5.1, Table 5). Approaches identified as necessary for managing described uncertainties, threats and barriers of biogas as a PtG concept are depicted on the horizontal axis and their frequency allocation is displayed on the vertical axis, relative to the total number of interviews per each sector approached in this study. As a means of comparison, the last bar in the individual measures represents the general frequency, based on all interviews performed in this investigation (n=27).

Besides politics, image campaigns were marked as essential techniques in risk management, but then, the interest of the stakeholders was, in general, to provide the public with information about PtG and biogas in a simplified manner. Overall, the stakeholders considered that the public lacks knowledge and may not recognize the differences between PtG and the conventional biogas sector. Furthermore, they believed that the public sees biogas and biomethane production as complex topics (cf. 5.5). Interviewed stakeholders feared that people oversimplify the innovation and assess everything as being the same.

As expected, scientists highlighted further research as vital to eliminate uncertainties in the development of the technology. This recommendation was mostly mentioned subsequently by stakeholders from politics, associations and finally by industry. The latter explicitly showed distrust to scientific work, categorizing it as much theoretical (cf. 5.9, stakeholders from industry).

Participants from all sectors rarely considered training and safe plant management as necessary actions for handling risks and challenges concomitant with PtG in biogas. Measures within this category were mentioned the least by stakeholders from industry and the most by participants from politics.

In several occasions, stakeholders from different sectors mentioned that they expect PtG to be a high-tech unit, so they understood that safety measures would be considered without any problem. Questioned experts debated that they have faith in existing safety regulations in the country, to which biogas needs to adhere; hence they perceived any potential accident as of low probability and relevance (cf. 5.4).

The establishment of more pilot projects and the design of viable business plans were also highlighted as necessary tactics among the stakeholders, but rather as to handle the challenges in the implementation of the technology. Notwithstanding, stakeholders from industry suggested this measure the least crucial within this category. Some of the participants from the industry shared that within their company they perform their business plans and market analysis, thus, they did not see the urgency of developing business plans.

Stakeholders from science

Some stakeholders in this sector demanded a kind of policy for land use, in which it is defined the extension to grow biomass as energy crops or for the chemical industry. Some considered that instead of reducing the support to biogas, the focus should be given to improving agricultural practices, progressing in the cultivation techniques and making them more environmentally friendly, e.g., by crop rotation. An environmental protection certificate was of interest for some stakeholders from science. However, they emphasized the fact that it needs to have an exact price. In this way, biogas plants are then identified as not only energy efficient but also environmentally responsible.

Moreover, stakeholders from science believed that politicians should support information campaigns to promote the public's acceptance in the PtG technology linked with biogas. Those stakeholders indicated that the biogas sector should take the opportunity of using the media to argue why PtG in the renewable sector mix is essential. The importance of the media in the formation of opinion in society was clear to most of the stakeholders from science. They indicated that an informed public would help influence politicians to fund the technology. However, stakeholders from science voiced that it is only a small share of the population that would be a participant in the diffusion of PtG because only a small fraction understands the chemistry and the notions behind this concept.

On this issue, an interviewee said: *“The stakeholders in biogas can try to solve this problem of biogas/biomethane value chain being a complex topic, by inventing good ways of communication.”*

In this line, some stakeholders from science identified certain agencies as crucial actors in the dissemination of information regarding the technology, like the Deutsche Energie-Agentur Gmbh (DENA) – the German Energy Agency. They expressed that such agencies should simplify the concept of biogas and PtG because they are very sophisticated technologies for the public. However, they also perceived the risk of over-simplification, which could provoke a wrong judgment of the technology.

Further, from communicating benefits, some stakeholders from science considered that people's opinion should be considered from the very beginning of the projects. and in the same way, the political mechanisms to support biogas should be transparent and clearly explained to the public.

Another aspect discussed by stakeholders from science was trust in politics as a means to secure investments in the sector. Since the energy policy has regularly been changing in Germany, these stakeholders suggested elaborating more stable, reliable and future-oriented energy policies. Stakeholders from science also complained about the amount of administrative work that producers must go through to apply for the subventions, “Bürokratie” – bureaucracy. In general, they advocate reducing instead the amount of paper-work needed to be done by energy producers.

All stakeholders from science accept as real that only facts count, in the form of a business model, as to say if PtG is feasible or not. Some participants indicated that even when the technology is not yet profitable, politicians should continue facilitating incentives for researching on it.

Pertaining to safety measures, various stakeholders understood that a good plant management is a pre-condition for the establishment of the concept of PtG. Based on that, they expect low risks of accidents and do not suggest any particular safety measure (cf. 5.4).

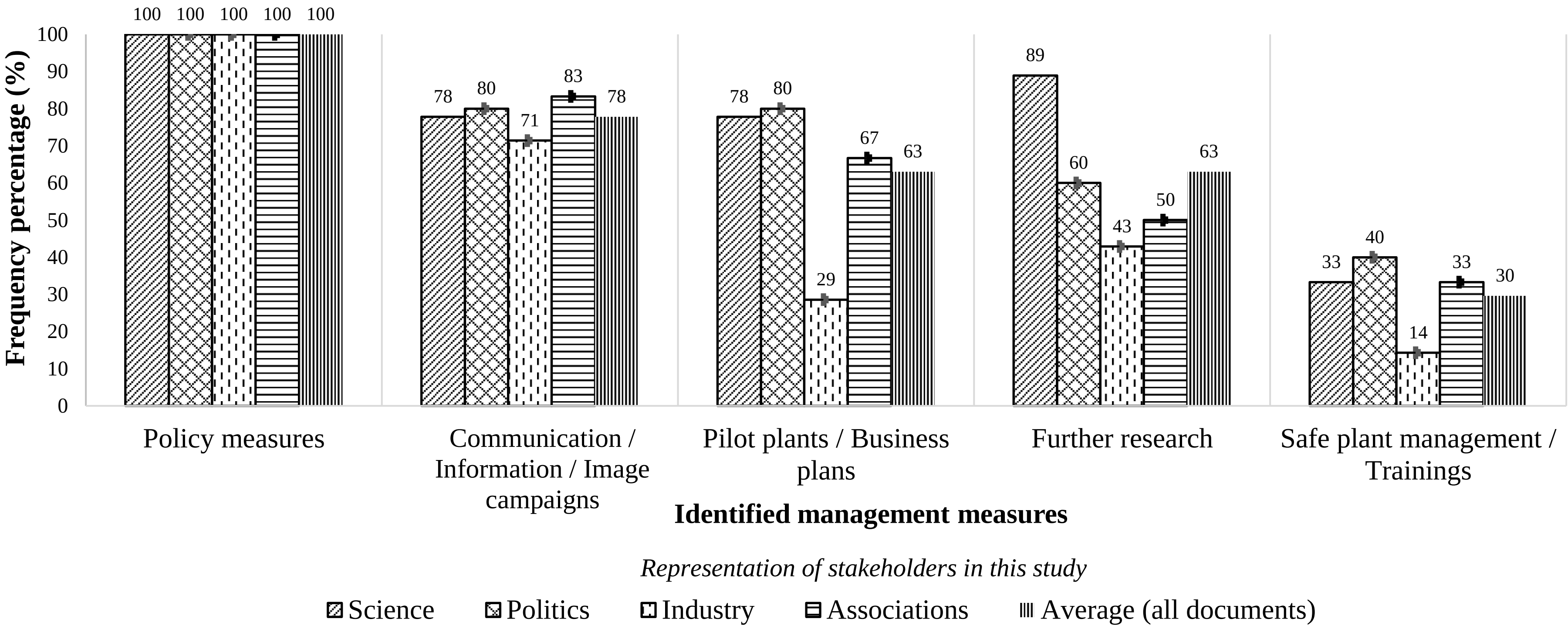

Figure 27. Percentage frequency distribution of suggested risk management.

Stakeholders from industry

Concerning measures to handle risks and challenges of implementing PtG in biogas, stakeholders from industry suggested education and advertisement (image campaigns) in general, to inform consumers about the benefits of the technology. They expressed that it is needed to call people's attention and explain the benefits cited (cf. 5.3). They specified that this communication could happen via media work, events, conferences, or through associations. Some stakeholders from industry indicated that for them it is imperative that biomethane be known as a green and sustainable gas. Some considered that the “Teller-Tank” discussion was just bad communication and the work of lobby groups against biogas.

In general, experts from industry are aware that the society needs to be included in the process of development of this technology in biogas. The considered that in order to change society’s attitude towards the technology, first, it is necessary to inform people about the advantages of PtG in the energy system. Then, they expect that the society will influence politicians to modify the framework conditions to make this technology prosper. Stakeholders from industry intensified that if the society is informed about PtG, people will believe that they are having a positive impact. Thus they will support it. For example, one interviewee said:

“People feel good if they believe that they are doing something good for the environment.”

Technology producers indicated that they provide instructions to biogas operators so that they can safely run the plant. They are optimistic that producers will be capable of handling PtG safely. They indicated that producers should consult them, as developers, on know-how; this way, they believe many technological risks can be avoided, including potential accidents.

Other stakeholders indicated that an understanding of the technology should be improved because this is an innovation not broadly known among biogas operators. Because of that, some stakeholders from industry were arguing that it is necessary to build demonstration plants, to show to the public and any interested producers how the technology works and what is the potential behind it.

In this sector, politicians are seen as the "makers", responsible of sustaining the biogas sector; thus, participants from industry believe that politicians should make possible the further development of PtG in biogas, especially through university research. Moreover, this support should be evident in bioenergy villages and sponsoring tests to see how it evolved. As one interviewee said:

"Such technology should be supported through meaningful projects, not only over the electricity price, which they redeem, but one has to analyze it a bit in a more comprehensive context."

When asked about their demands for an ideal policy to support biogas, the stakeholders surprisingly did not to have a defined perspective on how it should be done. An issue that they highlighted is the difficulty they found in the past with the biogas sector, about the constant changes in the regulations. Political conditions are seen as a limitation and problematic for the development of biogas and PtG.

Stakeholders from politics

These stakeholders highlighted the relevance of communicating with all stakeholders in the biogas sector. They pointed out that this would be an essential aspect because both the acceptance of this technology in society depends on, e.g., the type of substrate used and the implications they perceive. Similarly, the economic feasibility is dependent on the input material. Thus, they indicated that these two aspects should be well aligned.

Similar to other participants, stakeholders from politics perceive the media as an important influencer in people's opinions. They accentuated the importance to cooperate with this sector, in order to gain trust and reception in society. Talking about this matter, an interviewee from politics said:

"It is needed to promote information from the media since it is an opinion-maker and mood makers as well."

Due to the high challenges posed in the operation of biogas plants, stakeholders from politics suggested emphasizing good plant management. They stressed on providing training for the safety of their plants. They also heightened the need to have more pilot plants, in order to observe the technology running.

Moreover, participants from politics referred to the need for elaborating business plans, showing different feasibility options. These plans are of relevance not only to biogas producers but also to politicians.

As one participant from politics said: "You must convince politicians with facts. You must make them clear; this is a way that makes sense for some reason. It costs a certain amount of money, but that is money well invested."

About measures to avoid pollutants, some stakeholders from politics suggested trying to compel manure producers to store their by-products in such a way that no methane is emitted.

Considering PtG as an innovation in biogas, participants from politics suggested that politicians should consider this concept and provide a kind of exceptional support for its further development and application. Though, when asked about their opinions for possible financial support mechanism to develop the technology, in general, participants from politics did not have a clear concept on the kind of instrument and its functionality.

Some stakeholders from politics were advocating for traditional funding means, such as direct support, or elaborating new ones, e.g., through CO_2 certificates. Nevertheless, some of them were skeptical about the actual CO_2 reduction potential of the technology.

Interviewed stakeholders from politics also agreed on the recommendation of stakeholders from science, to keep funding research for the application of the technology, but for particular industrial use and to define working conditions joint with policymakers.

Stakeholders from associations

In this sector, participants were centered on designing biogas as independently as possible. Various stakeholders discouraged the idea of demanding political support, different to other sectors that took part in this study.

Stakeholders from associations expressed that incentives from politics should be directed to research and development. They believed that the technology should be developed by itself in order to be competitive (cf. 5.8, stakeholders from associations). In the long term, these stakeholders expressed that it is not sustainable to subsidize biogas producers, because ultimately the society would pay for it.

Moreover, some of the participants from associations uttered that if one makes a life cycle assessment, one will notice that the technology is resource intensive and probably worse than any fossil process. This way, they were expressing their uncertainties about the current competitiveness of the technology.

Concerning measures to handle safety issues, stakeholders from associations indicated that there could be human errors that may lead to risks. These experts explained that such human-generated risks could be avoided, if people are trained and informed about the potential hazards in the management of the technology. From the technical point of view, they emphasized that it is essential to follow security rules like the Technischer Überwachungsverein (TÜV) – Technical Inspection Association, which are to some extent already existent.

Based on purely technical aspects, some stakeholders from associations indicated that for the implementation of PtG, it is necessary to have clusters of producers, either companies for themselves, or farmers in cooperation with companies or among themselves. This recommendation was provided as a measure to assist producers in managing biogas as a PtG technology and avoid this way any potential accident.

In addition to these measures, some participants from associations also mentioned the need to have more pilot plants; and, to promote communication campaigns to promote more acceptance of the technology in society.

5.11 Remaining knowledge gaps

Interviewed stakeholders manifested uncertainty and unawareness concerning specific topics associated with the requirements and implications of adopting PtG in the biogas value chain. Table 8 provides a summary of the topics in which the stakeholders showed uncertainty, including those aspects in which they considered there is still need further scientific elucidation. Those topics are grouped within the following main topical sections: i) sociopolitical aspects; ii) technological development & economic feasibility; and iii) environmental impact assessment.

Table 8. List of research topics obtained from the expert interviews.

Category	Research Gaps
Sociopolitical Aspects	▪ Characterization of efficient means of communication on benefits & risk management of PtG in biogas ▪ Analysis of different policy measures for efficient support to implement PtG in the biogas value chain
Technological Development & Economic Feasibility	▪ Identification of suitable biogas plants for the concept of PtG (Comprehensive criteria) ▪ Further tests to improve the technology's performance ▪ Extensive economic assessment of a PtG-biogas concept, contemplating the whole biogas value chain and in comparison, to other notions for energy storage technologies or uses of excess RES
Environmental Impact Assessment	▪ Assessment of the actual CO_2 saving-potential of integrating PtG in biogas assisted with a Life Cycle Analysis (LCA) (Multi-parameter)

In general, interviewed stakeholders were thoughtful about an existent negative attitude in society towards biogas, which could extend to PtG. For them, this is of especial distress if this innovation is promoted to be deployed in connection with the biogas sector. Concerning the political support, examined stakeholders did not abundantly explain how an ideal political funding mechanism for biogas as a PtG technology be arranged. Nevertheless, they were convinced that biogas should have the opportunity to continue growing as other renewable energies are. On that account, they suggested designing research proposals contemplating the analysis of various political instruments aiming at financially assisting the biogas sector. At this moment, detailed models could provide a guideline of possible effective tactics to develop the sector promoted with political incentives.

Another element heightened by the stakeholders was the designation of criteria to help identify biogas plants fitting to the concept of PtG. Such taxonomy can help select optimal biogas installations to carry out PtG. Moreover, they advised assessing the CO_2 saving potential of this technological concept and the overall environmental impact of transforming the biogas value chain with PtG. In the following sections, the author refers to the arguments of the interviewed stakeholders per sector, regarding topics they ponder require scientific attention.

Stakeholders from science

These stakeholders agreed that there is much research going on nowadays in biogas and PtG. Nevertheless, they expressed that further research is always advisable. Thereby, stakeholders from science suggested to continue investigating in the following aspects:

Efficiency and technology performance: They punctuated that it is necessary to build demonstration plants since it increases the portfolio of the biogas sector. Though, having those model installations does not mean that biogas will be supported automatically; it has to demonstrate to be cost-efficient. Also, they indicated that it would be interesting to analyze the potential of PtG in small-sized biogas plants.

Economic feasibility: Electrolyzers are now the bottleneck of the technology, as indicated by the participants from science. Thus, they stressed on finding ways to build cheap and easy to handle electrolyzers. Some experts argued that it would be difficult for this technology to find political support if there are low-cost energy storage technologies, competing with PtG.

As they said: *“Politicians will wonder: why would you put your money into something that is expensive... and potentially not resource efficient? They will question that before talking about any incentives, market interference or quota system.”*

Means of communication: As quoted from them *“Information is always a recommendation one can give and is a straightforward one.”* They emphasized finding ways to inform the public about what is PtG and the benefits linked with it.

Viable land to grow biomass sustainably: They denoted that the discourse of land use could remain, thus they said it would be ideal if biomass for biogas is grown in the less fertile land, posing less competition for agricultural production. However, such a concept needs to prove to be profitable. They advised looking at not so good and contaminated lands to grow Miscanthus. The stakeholders emphasized the use of alternative feedstock for biogas and finally, biomethane production.

Assessment of potential environmental impact: Not only about the potentially harmful consequences, but also positive outcomes from the implementation of the technology should be assessed, e.g., if it is possible to increase biodiversity, support water protection and use fewer fertilizers versus a conventional agricultural production.

Stakeholders from industry

Participants from industry emphasized evaluating embedded environmental services & impact assessment. The stakeholders highlighted the importance of investigating the actual CO_2 reduction potential from PtG in connection with biogas. Some indicated that they run their LCA to know the GHG saving potential from the technology. On the one hand, some stakeholders from the industrial sector asserted that PtG in connection with biogas is almost carbon neutral. On the other hand, they did not provide any documentation to demonstrate it.

Besides, there were stakeholders from industry who indicated that it is difficult, or almost impossible to be completely carbon neutral because there are additional inputs in the production process that need to be considered, like for the construction of the plant and for the cultivation of the biomass.

Fair means of compensation: Experts from industry stressed the need to find alternative ways to remunerate the generation of biomethane in biogas plants. For example, one interviewee said: *“Such technology should be supported through meaningful projects, not only over the electricity price, which they redeem, but one has to analyze it a bit in a more comprehensive context.”*

Stakeholders from industry mentioned services provided by biogas and PtG, regarding environmental protection, which they stressed need to be compensated. Their recommendation is aimed at assessing and identifying possible policies to support biogas in connection with PtG, as a service provider of both energy and GHG emissions reduction.

Strategic ways of political support: Stakeholders from industry suggested assessing the scenario, in which the government makes natural gas more expensive, making this way biomethane more attractive. Results of such a model could help recognize the potential competitiveness of biomethane in the energy market. Nevertheless, when asked about their demands for such an ideal policy, overall the stakeholders from industry did not express any clear viewpoint on how it should look like or how it should be implemented.

Approaches for dialogue and ways of argumentation: In addition to subsidies, stakeholders from industry advocate for studying effective methods to communicate with other public. These stakeholders emphasized that knowledge about PtG in biogas need to be spread so that people can better understand what is meant with it.

Stakeholders from politics

Experts from politics highlighted assessing the economic feasibility of PtG in biogas. For some participants from politics, there are still uncertainties about the profitability of installing PtG and running the plant only in moments of excess energy or deficits. They indicated that there is a need for more detailed information in this regard.

Identification of appropriate incentives: Some stakeholders from politics indicated that biogas or any other renewable energy technology could be developed in such a way that it does not need any subsidy, mainly because people's acceptance is low when the energy prices are high. However, for the case of biogas, it will be challenging to grow in the sector without the appropriate incentives. Thus, they appeal for assessing possible support schemes for biogas.

Technology performance: Participants from politics stated to be interested to know the requirements necessary for installing PtG in current biogas schemes and its performance running with biowaste.

Stakeholders from associations

Among participants from associations, there was an emphasis on technology efficiency and use of substrate. They criticized that some sectors make their assessments on the benefits of the technology assuming that CO_2 is available and disregard the type of substrate to use. Hence, stakeholders from associations suggested investigating the potential of PtG using different input materials.

Competitiveness of the innovation: Some indicated that the comparison of PtG versus other technologies should include not only cost-benefit analysis but also an environmental assessment, especially about GHG emission reduction potential. Moreover, they emphasized on assessing the investment costs of this innovation versus other uses (H_2 or including its use as a platform chemical) and technologies. They still miss information about the applicability of this technology to small sized biogas plants.

Evaluation of potential environmental risks: A constant environmental risk is biomethane leakages. As part of a GHG assessment, they highlighted to analyze if biogas in connection with the electrolyzer could lead to more environmental risks.

5.12 Summary and typology of stakeholders' perception

In this subsection, the participants' perception of risks, challenges and uncertainties of adopting PtG in biogas are reported in a succinct manner, organized by their respective sectors. Table 9 displays a characterization of the perceptions found among interviewed in this study. The content is displayed per sector (vertically) and subject (horizontally).

Stakeholders from science

Participants from research institutions accentuated the technical benefits of incorporating PtG in biogas. They believed that this innovation would assist biogas to demand less land since biomethane conversion efficiency is improved. However, they indicated that more research is needed to further enhance the technical performance of the concept.

Despite this potential, some stakeholders indicated that accidents and gas leakages in biogas facilities would continue as long as the plant management is not improved, pointing primarily to farm-based biogas plants. Apart from that, these stakeholders showed high confidence on regulations as a means to keep risks of accidents under control. They also referred to the long-time experience of operators dealing with explosive gases as assurance of their capability to manage PtG.

Within this group was common to find opinions appealing for political intervention to support the PtG technology connected with biogas. They identified missing political support for the sector as highly critical and stressed that instruments to promote this energy concept are lacking. These interviewees believed that politicians are influenced by lobby groups, who then pass on their viewpoints to the society. They also highlighted a low willingness to pay in public and accentuated that the media generalizes accidents and only focuses on the mishaps of the sector, creating an unfavorable attitude in people. They also believed that the general public lacks the knowledge to understand the complex topic of PtG and its benefits.

These participants foresee a replacement of farmers as energy providers with highly industrialized facilities and specialized operators. In regard to technological challenges, participants from science focused on the various energy losses in the conversion steps to biomethane and on the uncertain scalability of the technology. Overall, these stakeholders were skeptical about the competitiveness of this concept. Politicians were broadly identified as main actors to deal with risks, challenges and uncertainties in this field, by providing a framework for financial support.

Stakeholders from industry

These stakeholders also showed high confidence in the performance of PtG linked with biogas and also emphasized its technical benefits. Besides, they showed high confidence in generating high-quality products from biomethane but expressed indecisions on the possible market response to those products.

Interviewees from industry identified farm-based biogas plants as highly vulnerable to accidents and depicted their operators as untrained. Because of that, these participants believed on a shift of energy providers under a complex concept of PtG in biogas, from farmers to highly skilled operators. They also expect no negative environmental impact from this energy model and displayed high reliability on existing regulations to manage risks.

They believed that previously reported accidents from biogas were the result of the lobby work of various interest groups in the energy sector. Participants from industry stressed the need to find alternative feedstock to generate biomethane.

These stakeholders perceived that the general public is ignorant and does not understand what biological methanation and PtG is and the benefits they represent. They used this argument to justify some of the criticism in society towards biogas. Thus, they were convinced that once people are informed about the advantages of the technology versus other energy generation and storage concepts, they will support the field. In this regard, they highly recommended increasing awareness in society on the benefits of this concept.

Participants from industry also identified a lack of political support in the sector, which they understand to be associated with the fears of politicians to lose popularity by supporting a highly controversial sector. Interviewees from industry also perceived that there is no support instrument to promote biogas and PtG as a climate protection technology or from a long-term perspective, seeing politics in the renewable sector as random and ambivalent.

These stakeholders also emphasized the various energy losses in this energy model, showed worries regarding the high cost and complexity associated with PtG and the challenges to expand the concept. Moreover, they exhibited uncertainty on the competitiveness of this energy storage notion. On this regard, they identified politicians and politics as a means to incentivize the technology and the field.

Stakeholders from politics

Among the participants from political institutions was common a skepticism about adopting PtG in biogas, requesting the installation of more pilot plants. They emphasized that this concept involves various sensitive topics in German society, e.g., land use for biomass generation, microbes from digestate spillages and accidents. They showed uncertainty on the economic feasibility of the concept, its technical performance and the identification of appropriate incentives to endorse the sector.

Similar to previous interviewees, stakeholders from politics perceived an uncritical environmental risk potential from PtG and biogas, exhibiting high reliability on existing regulations. Some of these participants showed skepticism in regard to possible impacts if the facilities are continued to be run with energy plants, in a conventional way. Stakeholders from politics also saw a risk of farmers as operators of this concept, arguing that this is a very complex topic for them that requires high care in plant management and safety control.

These participants believed that once people know about the benefits involved in PtG and biogas, they will support the technology. Currently, they believe there is still a negative public perception of the sector in the general public, which they believe will persist even after adopting PtG in the field. Participants from politics understood that this public criticism is the result of distrust in the population, highly influenced by negative press on the biogas sector. Various participants from this sector believed that the German energy politics is influenced by lobby groups and that currently, there is no favorable policy to support biogas or associated innovations, like PtG. On this subject, they showed high skepticism about the competitiveness of this energy notion due to the high costs involved and missed political backing. Besides, they emphasized that as long as the energy production relies on energy plants, sustainability aspects will remain critical.

Interviewees from politics identified scientists as main actors to deal with risks, challenges and uncertainties in the biogas industry & PtG, providing decision-makers with information on these subjects and on the state of the art of the technology. Besides, they identified social scientists among the group providing advice to politicians and stated that biogas operators are responsible for risk management in the sector. For them, the politicians' role is to provide sufficient funds for developing projects for the progress of the technology. This group also emphasized improving communication with the public to promote its support.

Stakeholders from associations

Interviewees from professional groups linked with biogas showed incertitude regarding the economic feasibility of adopting PtG in the sector. They emphasized the economic benefits of the concept but stated that it should be also available to small biogas producers.

Risk management for these participants consisted of following existing regulations to keep environmental and safety risks under control. These participants believed that PtG would not solve the problems in biogas concerning maize demand and land use impact. They indicated that some environmental problems and criticism in society would continue, if producers do not manage their plants safely and if they do not follow sustainability practices.

Like the previous stakeholders, participants from associations believed that farmers are not competent enough to handle biogas and PtG, thus seeing them as a high risk for the sector. Overall, these stakeholders foresee a low risk of environmental impact is there is a shift in operators; there could be some gas leakages, but they emphasized regulations to control them. Besides, they trusted on the experience of the biogas workers to manage digestates and reduce risks of dispersing unhygienic material into the environment.

These participants believed that there is still a negative attitude in the population towards biogas. Thus, they saw necessary an early public integration regarding any further project. They also alleged that the media has oversimplified matters in biogas, generalizing accidents as if they were happening in the entire sector, communicating this issue to the public. They perceived the media to be unfair, showing only accidents and not the benefits of the sector.

Similar to other stakeholders, participants from associations believed that politicians are influenced by lobbyists, but also by the reaction of some societal groups. Considering this environment around the technology, stakeholders from associations stated that political support, means to handle risks, challenges and uncertainties in the sector, should be in the form of research and development. They also showed high concerns regarding the competitiveness of this concept due to the high costs involved.

Among the technological challenges, interviewees from associations stated that access and availability to sustainable input material (carbon source) are necessary. They also showed uncertainty regarding potential impacts derived from this concept, the associated energy losses in the conversion steps and the feasibility to upscale and expand the technology.

Table 9. Typology of the stakeholder perception.

	Sector of the Stakeholders			
	Science	**Industry**	**Politics**	**Associations**
1. Benefits of PtG in biogas	Optimistic	Entrepreneurs	Skeptical (Need more pilot plants)	Uncertain about economic feasibility
2. Environmental and safety risks	Confident: no risks (Experience; no farmers)	Bureaucratic (Existing regulations protect against risks; no farmers with PtG)	Convinced: no risks (Experience & existing regulations; no farmers)	Convinced: no risks (experience & existing regulations; no farmers)
3. Societal opposition	Low willingness to pay; Media generalizes accidents in biogas	People are unaware (ignorant)	People distrust; Complex topic	People have low environmental awareness; Media oversimplifies
4. Political concerns	Lack of support; Politicians influenced by lobbyists; No long-term politics	Missing popularity; random politics; Influenced by lobbyists;	Lobby; Lack of funds; Missing appropriate support mechanisms;	Stigmatization; Influence from people and lobby groups
5. Technological difficulties	Scalability; no farmers; energy losses; competition	PtG complex; energy losses; scalability; no farmers	PtG for specialized plants; energy losses; competition	Input material; Competition; Scalability

Table 9 (Continuation). Typology of the stakeholder perception.

	Sector of the Stakeholders			
	Science	**Industry**	**Politics**	**Associations**
6. Economic barriers	Low willingness to pay; not competitive; no financial support	Missing political incentives; not competitive; uncertainty on substrate	Not competitive; substrate mix (less efficient)	Low willingness to pay; substrate mix; not competitive
7. Actors to manage risks and challenges	Politicians (framework); operators (safe management)	Politicians (incentives)	Scientists (Infor. on state of the art; avoid social conflict); operators	Politicians (no autonomy); media/news
8. Risk management options & measures to deal with barriers	Reliable politics; knowledge to people	Politics; knowledge to people	Safe operation; better communication; fund projects (R&D)	Politics (incentives); follow safety regulations; knowledge to people

Chapter 6. Discussion

6.1 Analysis of the findings in connection with other empirical studies

6.1.1 Benefits of integrating PtG in biogas

Interviewed stakeholders assented on various technical and economic benefits of integrating PtG into the biogas value chain. However, they did not elaborate on how the rationale of this technological concept aligns with societal expectations for its deployment or with prevailing legitimate interests in the German population. This aspect is discussed in detail in section 6.2.1, employing the social constructionism of a technology as theoretical framework.

Regarding the technical benefits of adopting PtG in biogas, referenced stakeholders mentioned primarily: i) the generation of biomethane, having a higher value as a platform substance due to its multiple uses in the industry, what they called “synergistic effects”; ii) flexibility for a long-term storage of renewable energy in the form of biomethane in the existing gas network, assisting this way a demand-driven energy provision; iii) compatibility of PtG with conventional biochemical processes in biogas (as BM); and iv) the utilization of CO_2 generated from biogas plants, avoiding in this form GHG emissions in the biogas value chain.

These advantages are in line with what has been reported in the literature about the technical performance of PtG in association with biogas (Bailera et al., 2017; Götz et al., 2016; Lehner et al., 2014; Lewandowska-Bernat and Desideri, 2017; Mazza et al., 2018; Rachbauer et al., 2016; Zabranska and Pokorna, 2018).

Stakeholders from science and industry agreed in their opinions, exhibiting an optimistic attitude towards PtG. They emphasized on aspirations of the technology, e.g., use of local feedstock, reduction of land demand and avoidance of additional investment to expand the national gas grid to store biomethane.

Conversely, stakeholders from politics and associations were moderate in their statements, emphasizing the relevance of improving the biogas process. However, they were considerably more critical when assessing PtG linked with biogas than the stakeholders from science and industry. The skepticism of the stakeholders from politics and associations was about: i) the economic feasibility of the technology; and ii) the technological performance (e.g., hygienization of digestate and demand of biomass).

Stakeholders from politics and associations suggested that there are few pilot plants established in the country and expressed their concerns to be currently unable to support this technology or its associated trade-offs entirely. Other stakeholders insisted on the benefit of potentially having less environmental impacts and a reduced demand for land from the biogas sector linked with PtG, as this technology promises to increase biomethane yields, thus, decreasing requirements for biomass as input material.

Impacts related to the production of biogas and its upgrading to biomethane were reviewed by Paolini et al. (2018). The authors discussed that benefits from the biogas sector are frequently restrained due to its accompanying adverse effects on the ecosystem in the form of, for example, leaked biomethane, nitrous oxide and carbon dioxide emissions and the release of unfermented digestate. These aspects cause social distress and could limit the expansion of the biogas technology and innovations linked to it.

A possible reason explaining the reservations of interviewees from politics and associations on the adoption of PtG in biogas is that they assumed social responsibilities to acquire a position on the technology. Their opinions and public support to a technique or innovation influences various societal segments, e.g., civil groups in the case of politicians and biogas producers with respect to both stakeholders.

The attitude of stakeholders from science and industry is comprehensible since they rely on the technology as part of their work: research (in the case of scientists) and business (in the case of stakeholders from industry). These professional motives could have influenced them to build a confident attitude towards PtG linked with biogas. This interpretation is exhaustively discussed in reference to the concept of expert roles and risk perception in section 6.2.6.

Other researchers assessing experts' perceptions on risks and benefits of energy technologies have encountered similar attitudes among stakeholders, such as those found in the present investigation. Harris et al. (2018) reported that a knowledgeable group, highly familiarized with the investigated technology showed a more encouraging position towards the technique, in contrast to participants from other fields and nonexperts. Besides, they found that among specialized groups, the benefits of the technology were more emphasized than the associated risks. These responses provided indications of experts posing high reliability on the field, their own "standards" and interests, eventually determining their risk perception.

Hunsberger et al. (2017) investigated the effectiveness of biofuels' promises, e.g., battle climate change, assure local energy provision and foster economic growth, by analyzing reported literature on the results of policies endorsing the sector in various regions around the world, including Germany and the EU. Biofuels are similar to biogas in the sense of pertaining to the bioenergy field and that biomethane can be used as a fuel in the transportation sector.

In the study of Hunsberger et al. (2017) was found that overall, biofuels do not fulfill all expectations posed on them, explaining that promises are usually expressed in ambiguous forms and limited in scope, not considering crucial side-effects, e.g., public perception of fairness on benefits distribution, conflicts between targets and not reflecting on how such contingencies should be handled under diverging interests. These authors recommend disentangling expectations among various subjects and aims, i.e., "*by theme, by scale, by time frame and by social characteristics* [of the influenced stakeholders]".

In view of these indications, it is proper to account for a comprehensive approach when reflecting on the benefits of PtG in association with biogas. Not only technical features should be emphasized, but also possible trade-offs in an all-encompassing manner. Ways to counteract potential risks should be reflected together with measures to assess the actual efficiency of the promised benefits and the distribution of both risks and benefits among all interest groups.

Furthermore, the alleged advantages of PtG linked with the biogas sector should also be specific enough to facilitate its benchmark towards clearly stated and attainable and success indicators, defined in a legitime and participatory manner. In addition, all advantages identified in the technology and innovation need to be regarded in a far-reaching scope and by using an inclusive assessment method, timely determining urgencies and identifying areas of potentially ambiguous or conflicting targets that could lead to social controversies.

6.1.2 Reception of biomethane as a platform substance

Biomethane is a byproduct derived in the processing and upgrading of biogas. With the implementation of PtG in this industry, it is expected to attain higher biomethane yields. This substance can be used in traditional sectors in Germany, e.g., in combined heat and power plants or as a fuel for transportation.

The adoption of biomethane as a promising platform material for the chemical industry attracts various groups since the emergence of new market niches helps diversify the business portfolio of the biogas sector, assuring a return on investment. In this section, the author analyzes the judgment of the interviewees in this study on the readiness and potential reception of biomethane in a biorefinery concept in the German context.

Interviewed stakeholders exhibited an evident skepticism about any positive reception of biobased (in this case, biomethane derived) products in Germany. They expressed substantial concerns about the willingness of people to buy biobased commodities, which have a higher price relative to conventional goods.

Overall, the participants of this study emphasized the need to communicate the environmental benefits of such biobased products, which they believe must demonstrate to be competitive in the market. The recommendations from the participants of the present investigation imply that knowledge about the benefits of biobased commodities would promote their acceptance among people.

Similar results were found in a study funded by the European Union Seventh Framework Programme. Experts suggested easing the disclosure of information with the public to facilitate the consumers' acceptance of biomass-based goods (Mirabal, 2013). The findings of this study are also in line with Kainz (2016), who performed surveys among German consumers and indicated that there is a limited understanding and even deceptive information about biopolymers (a type of biobased material) in this context. Furthermore, Rohracher et al. (2004) reported that various terms referring to bioenergy and biomass-use might be too complicated or abstract for the general public.

Similar to the suggestions from experts in the present investigation, Kainz (2016) concluded that significant effort is necessary, both from politics and the industry, to inform people about the characteristics and benefits of bioproducts to promote their positive reception in the country.

Fytili and Zabaniotou (2017) also suggested that the reception of bioenergy and its derived products is facilitated in society by increasing understanding in the public about the consequences of climate change and the benefits of environmentally friendly products and technologies. In addition, these authors indicated that promoting an attitude of equity and participation when deciding on the adoption of a technique or an innovation are similarly helpful when seeking for its societal reception.

Another aspect is that in the production of biobased commodities there is a potential for aggravating environmental externalities. Kainz (2016) indicated that for example “durable biopolymers” may not be necessarily perceived as environmentally friendly in German society since people are aware that they may pollute the environment if they are not properly recycled or burned.

An additional argument that could explain an unfavorable attitude towards biobased commodities derived from biomethane/biogas is the damaging advertisement and general controversial public opinion of a similar field, i.e., biofuels (Cacciatore et al., 2012). People may hold a less positive imaginary towards sources of energy demanding biomass for their generation, such as biomethane produced from biogas and sourced from energy plants, similar to reports presented by Rohracher et al. (2004). This mental model may lead people to consider both industries as similarly environmentally damaging and ultimately choose to reject them. Details on technology stigmatization & risk perception together with potential implications for the biogas industry are presented in section 6.2.3.

Concerning how people feel about and related to biomass-based products, Sijtsema et al. (2016) conducted a focus group discussion among 89 participants from the Czech Republic, Denmark, Germany and Italy. They found that people identify biobased commodities as unusual and when they reflected on the concept, their participants encountered complicated feelings both positive and negative ones.

The researchers of that study indicated that ambivalent sentiments provoke hesitation in people, mainly due to their limited understanding of the new concept and their slight acquaintance with the innovation linked with biobased commodities. Moreover, those researchers observed that participants of their study thought carefully about the full complexity of a biobased value chain when they formed their perceptions and generated more complicated assessments about them (Sijtsema et al., 2016).

As suggested by the participants of the present investigation and as indicated in various studies on the acceptance of bio-based/biomass-derived products, providing information to the public on their benefits and characteristics could facilitate a positive reception. This practice could assist in finding alternative market options for the biogas industry.

6.1.3 Challenges in the renewable energy policy

A critical aspect emphasized by the stakeholders interviewed in this study was the uncertainty they perceived in the political landscape surrounding renewable energies in Germany. Stakeholders from industry identified as a risk for their business that currently there is no economic instrument to support biogas in combination with PtG as an energy storage mechanism or as a climate protection technology.

Similarly, stakeholders from science believed that there is a lack of interest or support from politicians towards the biogas sector, generating uncertainty investing in the industry. In addition, experts from industry and science had the conviction that there is no long-term policy for renewable energies in Germany since politicians have frequently been changing the regulatory support mechanism, the EEG. They expressed that this situation generates incertitude for investors, who go elsewhere, where there is more stability for their businesses. Variability in political frameworks has also been categorized as a vital source of hesitations in renewable energy projects (Lee and Zhong, 2015).

Besides stakeholders from industry and science, some participants from political institutions indicated that the future of PtG and biogas is indetermined if there is no public funding available. These stakeholders also explained that politicians might fear supporting biogas because they could lose popularity.

In a study assessing uncertainties in clean energy policies across European countries, Purkus et al. (2017) indicated that support mechanisms that aimed at stimulating the growth of the bioenergy sector in Germany have experienced significant and diverse changes over the last 17 years, corroborating to the statements provided by the experts of the present investigation.

Purkus et al. (2017) added that these modifications in the EEG were the result of disputes on failed promises of this sector to achieve cost reductions and to remain coherent towards sustainability standards dealing with biomass as feedstock to render bioenergy.

These authors also explained that promoting policies in the bioenergy sector confronts various challenges, such as insecurities in cost reduction, assessing and managing potential effects in environmental and social systems and plausible modifications in the energy context, i.e., in relation to latest shifted political interest in flexible energy supply versus continuous mechanisms.

As a lesson learned from the experience of the German and overall European bioenergy regulations, Purkus et al. (2017) understand that those policies have been enacted missing coherence and completeness, demonstrating narrowness in its scope. They argued that those policies proposed various aims, e.g., assurance of energy supply, combat climate change and the promotion of economic growth in rural areas and overall trade and industrial development. However, those goals were not ranked based on any priority, which was reflected on increasing antagonism among the different goals and incoherence with other social targets. The continuous changes of focus in the bioenergy policy translate into uncertainty in the market sector and subsequently in an increased risk perceived among business people, affecting their readiness to embark in bioenergy projects.

Besides, the ambiguous and changeable prioritization of the aims in bioenergy policies was also reflected in inconsistent support for research & development and dissemination of technologies, according to Purkus et al. (2017). These authors suggest decision-makers to recognize the side effects of their policies from its beginnings and define less ambiguous "hierarchies of aims" in their focuses.

Rosenow et al. (2017) also propose to elaborate more thorough policies aiming at energy efficiency, with more explicit target definition, considering the high complexity and expenses involved in energy efficient technologies. They advocate for a policy mix that can support the different features of clean energy mechanisms and their adaptation to multiple sectors.

In this consideration, less changeable bioenergy policies, supporting key characteristics of technological innovations, such as flexible energy supply and climate protection, are beneficial for the continuity of the industrial sector, which is reflected in less volatility in the market.

Nevertheless, both stakeholders, policy-makers and promoters of technologies, i.e., researchers, associations and business people, need to consider a broad and far view on the scope and aims of support mechanisms for these technologies and the associated implications of such policies.

This consideration should include potential risks to the environment and in reference to potential responses of societal groups. This way, more comprehensive and resilient support instruments of energy storage and efficiency technologies, such as in the case of adopting PtG in biogas, are promoted in the country, leading to less uncertainty and controversies.

6.1.4 Competitiveness of biogas and PtG and expected political response

All stakeholders agreed that biogas and PtG compete with other technologies and products demanding excess renewable electricity or that could be more efficient in their energy conversion pathways.

In respect to competitiveness, Götz et al. (2016) indicated that the relatively low productivity and increased costs of PtG are significant disadvantages of this technology. The cost-effectiveness of PtG is of high importance for the interest groups behind this energy storage concept, who need to demonstrate the relevance of this innovation to potential investors.

In addition to this challenge, interviewed stakeholders of the present study concurred that there are energy losses in every conversion step of excess renewable electricity into biomethane, which they understand makes PtG less competitive to other technological concepts. These thermal energy conversion losses have been reported in a technical study published by Götz et al. in 2016.

Interviewed stakeholders from politics in this study highlighted a growing criticism to use biogas as the favorite manure treatment technology, in contrast to low-cost and easy to handle approaches like conventional storage tanks, aimed at pasteurizing manure, as indicated by Schoenau and Assefa (2004).

Stakeholders from science and industry believed that PtG, similar to biogas-derived biobased products (cf. 6.1.2), should thrive in the market without any political intervention. This attitude could be related with the interest of people from industry to continue in the biogas business but different than before, without demanding or receiving subsidies since that practice was broadly criticized in the past both national- and internationally.

Moreover, maize monocultures became characteristic of the biogas sector, which was communicated as an indirect result of the energy policy promotion, through subsidies part of the EEG in Germany (Bayerischer Rundfunk, 2016; George, 2016; Mihm, 2011).

Stakeholders from science may come to the same conclusion as a reasonable interpretation of studies in which it was demonstrated a substantial increment in prices of agricultural land and products. Moreover, critical structural changes in the food market occurred due to subsidies supporting biogas from energy plants, primarily maize, causing this way crop substitutions (Appel et al., 2016; Britz and Delzeit, 2013).

Similar to stakeholders from industry and science, some participants from political institutions suggested letting biogas & PtG become competitive by itself. Likewise, some stakeholders from associations expressed that political support pursuing an increase of competitiveness in the sector should only be available for research and development and nothing else. This is an attitude to be expected from participants in politics and associations due to the controversies biogas experienced in society in liaison with subsidies promoting its growth.

Nevertheless, there were few stakeholders from politics and some from associations, who believed that political measures should be implemented as mechanisms to promote the implementation of PtG in the biogas industry, such as minimum quotas of biomethane use or CO_2 certificates in various sectors. They believed such measures support the development of technologies and approval of products derived from biogas.

It is reasonable that these stakeholders want to remain in the status quo, continuing the biogas business model as it was habitually running. Some stakeholders from politics may support the idea of creating incentives to promote biobased products, believing that this is a pioneering business that could be activated.

The same reason could be related to associations, which may be looking for business opportunities, especially after the previous fixed EEG contracts are fading away. Stakeholders from associations argue that jobs could be created and new market opportunities for biogas producers could be materialized. Financial means could facilitate the establishment of the biogas value chain, including biobased products, having biomethane as key raw input material.

Another aspect is the based feedstock for the energy generation behind this energy storage concept. Overall, the stakeholders that took part in this research agreed that PtG in association with the biogas sector seems not to be economically competitive in contrast to other renewable energies and fossil fuels. They also indicated that biogas may still require energy plants to be feasible for producers and insisted that in case of shifting to manure and biowaste as input material, the production costs would be significantly high.

This aspect means that if biogas continues needing energy plants counting on a PtG concept to be economically feasible, certain boundaries would need to be set to avoid negative consequences, as reported and severely criticized in the past (cf. 3.1).

Other studies have come to similar inferences regarding the biogas industry and the use of biomass for bioenergy (BMU and BMELV, 2009; Meyer et al., 2018; Schröder et al., 2018). These reports have suggested, for example, the use of agricultural residues instead of energy plants and obtain biomass from marginal lands, to make the bioenergy generation and its byproducts more environmentally friendly.

On this point, it is important to consider that there is a political priority in the European Union to promote the bio-industrial sector in the region. Dupont-Inglis and Borg (2018) registered, for example, a list of opportunities envisioned in a European bioeconomy, which includes among others the maintenance of a competitive labor force in the regional biotech sector and enabling trade prospects to biomass suppliers. All these aspects could benefit biomethane producers, by assisting, for example, the biogas industry with a favorable political environment, investment options and incentives.

Integrating the concept of PtG into the biogas value chain provides various opportunities in the industry and the economy in general. However, environmental, socio-political, technological and economic concerns should be recognized and faced, which should be acknowledged among all interest groups, when discussing means to promote the competitiveness of biogas linked with PtG.

6.1.5 Safety and environmental issues in biogas installations

In general, cross-examined stakeholders regarded farm-based biogas installations as examples of cases in which environmental and safety risks of the biogas industry relate to a disregard of existing safety regulations. In this way, interviewed stakeholders assumed an elitist attitude, shifting any blame of mismanagement to farmers and accusing them of not being adequately informed to operate their biogas plants, representing a risk for more complex technologies like PtG, if being indiscriminately adopted in biogas facilities.

On this subject, a regional manager of the Fachverband Biogas, a leading association of both small and industrial-scale biogas producers in Germany, expressed in a newspaper that biogas plant operators, including farmers, inform themselves in a regular basis and that biogas workers are required to attend safety training courses. He added that in general, biogas operators are very interested in getting updated on the technology. However, he pointed out that there are always some of them who do not attend such training (Zacher, 2018).

In that newspaper was also published, that currently there are more than 400 legislations which biogas operators have to bind to. However, the representative from the Fachverband Biogas expressed that those regulations are confusing for most of them. Moreover, he indicated that the institutions responsible for auditing the biogas installations have critical personnel deficit, leaving all the risk management responsibility to biogas producers (Zacher, 2018). This situation aggravates the safety problem of inadequately managed biogas facilities.

As a whole, interviewed stakeholders in this investigation showed high reliance on safety regulations as a mechanism to avoid accidents and for dealing with environmental risks in biogas plants, including those associated with a PtG technology. Despite their high confidence on regulations, mishaps have been unceasingly documented linked with biogas installations in Germany and disregard of the existence of multiple safety and environmental protection regulations in the country (cf. 3.1). Different from generally believed by the interviewed stakeholders, those accidents have been reported to occur both in industrial as well as in farm-based biogas plants.

Examples of accidents from farm-based biogas facilities include the death of an operator in Weißenburg (Bayern) and Nienburg (Niedersachsen) in 2017 (Eckinger, 2017), other accidents occurred in Kißlegg (Baden-Württemberg) in 2016 (Eckinger, 2016) and Redwitz (Bayern) in 2014 (Hauser, 2014). Similarly, there have been mishaps reported from industrial biogas plants, as the discharge of various liters of slurry in Engstingen in 2017 (Keck et al., 2017), in Rhadereistedt in 2005 (Die Welt, 2005), in Wuthenow in 2017 (Grunow, 2017), in Brokenlande (Schleswig-Holstein) in 2018 (Friederichs, 2018) and back in 2014 (Leng, 2014).

As a means of accidents' prevention, scientists accentuated establishing more pilot plants and providing more funding for further research in the PtG technology linked with biogas. In general, the stakeholders seldom mentioned the establishment of reliable plants and safe management as preventive measures against accidents in biogas and PtG. Stakeholders from industry especially least mentioned this topic, despite the accidents that have been reported happening in the biogas industry.

This attitude can be explained by their belief that with existing safety regulations there is no need to fear risks (cf. 6.2.2). In contrast, stakeholders from politics put more emphasis on safe plant management and provide safety training to biogas operators. This view of the stakeholders from politics corresponds to their expected protecting role, further details in section 6.2.6

Regulations alone cannot prevent accidents since they need to be implemented in the usual management of the biogas facilities. Besides, having regulations as a unique form of management, without a strategy for monitoring and public disclosure on risk control, stakeholders may underestimate critical risks in the biogas production and also how trust in them is eroded in society as accidents continue to happen. These aspects could eventually lead to further misfortunes in the industry after implementing PtG and ultimately, may raise more societal controversies.

A study of Casson Moreno et al. (2016) reported that a low-risk perception among biogas producers is an important cause of accidents in this sector. A neglection of risks in their biogas facilities may lead operators to believe that safety training are not urgent or are even unnecessary.

Kabasci et al. (2012) interviewed various interest groups in biogas, including farm-based biogas operators, aiming at analyzing their opinions on the sector and their management practices. Results of that study showed that 59% of the biogas workers & administrators mentioned they had not attended any seminar for improving the safety of their facilities. This situation occurs despite the requests of the Farmers' Association, urging biogas producers to attend regular workshops on safety management.

Biogas operators indicated instead that they read some literature, learned from other producers and from their own hands-on experience on how to control safety and environmental risks in their installations (Kabasci et al., 2012). The opinion of the stakeholders in the present study corroborates in part of the German biogas reality: absence of appropriate and sufficient safety training among biogas operators. This situation is evidence that calls for attention to decision-makers and risk managers related with the biogas industry.

Safety training should not only be mandated, but also facilitated to biogas operators, especially to producers aiming at implementing a PtG concept, i.e., a safety training in an uncomplicated and a practical manner. This measure would then serve as a precautionary approach to handle risks of accidents and of environmental damages from the biogas sector (cf. 2.5).

The present investigation provides further proof on the urgent need to increase risk awareness among stakeholders dealing with biogas facilities. It is thus reasonable to verify and align the content of the training provided to biogas producers, to consider not only technical specifications for safety measures; but also to promote their understanding on factors influencing the formation of a certain risk perception among biogas operators, which may influence their usual risk management measures.

In this manner, biogas producers could be made more alert about dispositions they have that may compromise the safety management of their plants, posing threats to themselves, their business, the people around their facilities and to the environment.

Another aspect that was discussed by the stakeholders was the possibility of maize monocultures to re-appear as an environmental issue and topic of debate in reference to the biogas industry since it strongly debated in previous versions of the EEG (cf. 6.1.4).

Interviewees emphasized that if biogas/biomethane production keeps relying on maize as its input material, maize cultivation would be required, thus potentially impacting the environment in a negative form and subsequently, risking being criticized anew in society. On this matter, Tschiggerl et al. (2018) performed a life cycle assessment of a pilot PtG concept, concluding that independent of the technical viability of the project, the basis for obtaining energy determines the environmental effects of running a PtG system.

In another environmental assessment of PtG, Collet et al. (2017) identified that running PtG in a fluctuating manner, sourcing renewable energy to continue the process can assist reducing GHG emissions from the energy system. However, in that study, the source of carbon from biogas installations to generate CO_2 feeding a PtG process was sewage sludge, different from the business as usual, which in the case of Germany is maize. Inferences on how environmentally friendly PtG could be linked with a conventional biogas value chain cannot be determined from that study.

The controversy of using biomass to source carbon could potentially extend to PtG, if maize is used as feedstock for biogas installations running with this technology. This is a subject that requires attention from decision-makers and risk managers within this sector. Further details on implications of this issue are described in section 6.2.3.

6.1.6 Expected actors to handle PtG and biogas

Concerning the foreseen actors involved in the management of PtG and biogas, stakeholders from science, industry and politics believed that the role of farmers as energy providers is probable to be displaced by companies with specialized and trained staff on biogas and PtG. Stakeholders from associations did not discuss this topic.

Most interviewees of this study perceived operators of farm-based biogas installations as untrained and incompetent, building and managing biogas plants unsafely (cf. 6.1.5). Overall, the stakeholders expressed fear to implement PtG in biogas plants located in farms since they perceived those installations as most vulnerable to accidents and built with least safety considerations. Similar statements accusing farmers of mismanagement and lack of training in the biogas industry have been reported in the various news (Deter, 2015; Thölke and Thöne, 2012).

Possible reasons behind this position among the interviewed experts of this investigation are that their attitudes towards farmers could be influenced by news reporting on accidents happening in farm-based biogas facilities. Another reason could be that there is a kind of disregard against farmers from some sectors, e.g., industry (from large companies), who may perceive farmers as competitors in their biogas business, hence choosing to discredit them. This way, the public perception of farmers may deteriorate, leading to social pressure and possibly their retirement from the sector as energy producers.

6.1.7 Stakeholders' uncertainties on incorporating PtG in the biogas sector

Concerning subjects requiring further research, influencing the competitiveness and diffusion of PtG in biogas, all the stakeholders suggested to investigate in-depth:

i) Innovative business models proving the economic feasibility and performance of the technology;

ii) Approaches to depicting potential environmental impacts of associating a PtG concept in the biogas value chain; and

iii) Identify fair and effective ways of political compensation of this innovation in biogas, emphasizing on its energy storage and climate protection services.

On this matter, van Leeuwen and Mulder (2018) ran various models assessing the profitability of PtG in the existing market settings, concluding that the technology needs viable business mechanisms. They suggested among others to continue the research on the optimization of the PtG technology to reduce production costs.

Besides that, van Leeuwen and Mulder (2018) accentuated defining premium markets for "green hydrogen" derived from PtG, as a way to incentivize the concept. Another business instrument recommended in that study was to keep renewable electricity price low, to compensate for the high production costs of PtG.

In an investigation performing system modeling and feasibility assessments of already installed PtG projects, Quarton and Samsatli (2018) also concluded that there is a critical need to determine viable business models for PtG. Moreover, the adaptability of PtG linked with biogas needs to be further understood, in addition to current energy systems and its impacts, considering energy fluctuations and regional variations.

Lewandowska-Bernat and Desideri (2017) described various of the challenges currently confronted by the technology of PtG, similar to the uncertainties posed by the experts interviewed in this study. Among those challenges, Lewandowska-Bernat and Desideri (2017) cited the need to identify regulatory instruments that assist PtG as an energy storage concept and to make available modeling data on PtG linked with the power grid to understand responses in the energy system. Besides, they emphasized the urgency of more case studies to comprehend economic and social requirements for adopting PtG.

In addition to these aspects, stakeholders from industry and science highlighted the need to find strategic ways of communicating with the public. All these topics reflect a kind of experience learned in the sector from all the aspects previously criticized in the biogas technology (cf. 3.1). Interviewed stakeholders also expressed uncertainty about the feasibility of the PtG technology to be upscaled from laboratories to the market.

These questions and challenges demonstrate incertitude among the stakeholders on this emerging technology in biogas, which could translate into/lead to a flight of potential investors if these issues are not adequately solved in a reasonable timeframe.

Ultimately, this situation would represent a loss of the potential benefits that PtG promises to bring as part of the biogas production process. Moreover, the uncertainties among the stakeholders demonstrate the necessity to have further research to understand better the technical potential, likely environmental impacts and the societal significance of adopting a PtG concept in the biogas industry.

From the statements of the stakeholders, one can perceive that biogas as a PtG technology is challenged not only to demonstrate its technical and financial feasibility and adaptability to the management skills of the various stakeholders, part of the biogas industry. It also has to prove its compatibility with societal interests and expectations.

6.2 Analysis of the findings in light of the theoretical framework

6.2.1 Links of technologies with the societal context

The responses obtained from the interviewed stakeholders signal that PtG offers a technological progress in the biogas industry purely. The participants provided few indicators of any advancements of this emerging technology in biogas regarding comprehensive means to facilitate the assimilation/association of discourses supporting this notion into/with socially ingrained values and interests, easing its acceptance, validity and co-development in public.

In connection with this finding, Mallett (2018) argues that innovations have been conventionally mismanaged. The author explained that emerging technologies, such as the concept of PtG liked with biogas, should be viewed considering not only their technical and economic benefits, but they should also be managed in reference to their sociocultural, environmental and political context.

In addition, the notion of “Social Construction of Technology”, proposed by Pinch and Bijker (1984), states that the success of a technology goes beyond its technicalities in regard to what experts refer to be optimal or beneficial. It is necessary to comprehend what the social environment surrounding a technology denotes to be favorable, which elements the various social groups and institutions consider to be relevant.

Such a comprehensive assessment leads social actors to a conclusion of what is a risk, or what is advantageous for the public in reference to a technology. Moreover, it is essential to identify which stakeholders are involved in this process of social construction of a technology and what their interactions are, in addition to understanding the meaning a technology has to the diverse social networks. When the influence of the context is assessed, it is then realized that various conflicts emerge since the various stakeholders possess different expectations, interests and meanings in connection with a technique.

These conflicts are associated with i) the expected performance of the system; ii) the suggested approach to solve technological problems; and iii) possible moral issues derived from the adoption of the technology, as perceived by the multiple stakeholders (Pinch and Bijker, 1984). In consideration of these aspects, risk managers and technology developers obtain an understanding of the social constructivism of a technology and how these factors affect its acceptance or rejection.

The social setting of a bioenergy technology, such as biogas, is a critical component to consider in its development and innovation since it influences the public reception (Soland et al., 2013; Wegener and Kelly, 2008). It is therefore required that stakeholders and decision makers of the biogas sector frame the opportunities of PtG and biogas in accordance with the societal demands and expectations of the German people. Considering that multiple social actors may have conflicting opinions about a technology and may also possess divergent depth of understandings on emerging concepts, it is also a role of decision-makers to introduce new topics in the society in an unbiased manner. They should thus create awareness about innovative concepts and in this way, balance societal trade-offs, promoting informed opinions among various interest groups.

In this line, stakeholders from science were very skeptical about the possible acceptance of biogas and PtG and emphasized that the sole introduction of PtG will not change people's opinion on biogas. In addition to stakeholders from science, some participants from politics and most from associations expressed skepticism about a possible welcome of PtG in the German society. Participants from industry and others from politics in the present investigation suggested that a good understanding of the innovation of PtG linked with the biogas process will help gain the support of people and increase their awareness on the relevance of these technological concepts in the local energy system and its role in the societal context.

At this point, it is proper to introduce the term legitimacy, which has been described as: *"the perceived consonance of an entity with its institutional environment, i.e. a socially constructed set of norms, values, beliefs and practices in its context"* (Markard et al., 2016; Scott, 2008; Suchman, 1995). Furthermore, the notion of technology legitimacy has been defined as *"a commonly perceived alignment (or misalignment) of a focal technology with institutional structures in its context"* (Markard et al., 2016).

Markard et al. (2016) proposed that as soon as people are informed about an innovation and start to advocate for its development, the legitimacy of a technology is strengthened, while the risk of being rejected is reduced. Moreover, Bergek et al. (2008) and Hekkert et al. (2007) indicate that legitimacy is a vital element for the progress of an innovation, e.g., PtG in biogas, since it assists in the provision of economic, political and social support, aspects that are broadly demanded by stakeholders in the biogas sector (cf. 5.5, 5.6 and 5.8).

Thus, the adoption of PtG in the biogas sector requires the consideration of legitimating aspects the social framework that surrounds the field, comprehending what the interests, motives and expectations of the different stakeholders are.

Understanding these valid aspects, developers of PtG and biogas, risk managers and decision-makers can integrate strategic elements in the design and promotion of this innovation in its social context. By doing that the cohesion of the technology is facilitated to its public context, aligned with the socially constructed standards of what is beneficial and how that innovation should be ingrained into their shared social systems and understandings.

6.2.2 Culture and its influence on risk perception and management

As stated by Renn (1998) and more recently with the concept of risk governance (IRGC, 2017), risk perception is a vital aspect complementing technical risk assessments. It assists in determining parameters to identify and evaluate what is risky from various stakeholders and to deliberate among various management options in reference to multifaceted outcomes.

Overall, interviewees of this study believe that there will be no severe environmental and safety risks in handling biogas installations associated with the technology of PtG. They indicated that there might be some risks of accidents due to explosive gases, e.g., H_2 and CH_4; however, they have faith on existing safety regulations to keep such risks under control, including the hygienization of the digestate. In particular, stakeholders from science emphasized that producers already have experience handling such gases. Thus, they foresee a little risk of explosion in biogas facilities connected to PtG.

Besides trusting on existing safety guidelines, the stakeholders relied on the available know-how and various years of practice working with the biogas technology to control any potential health and safety danger or environmental threat.

It could be understood that professional interests may have influenced stakeholders that participated in this study, who are experts in biogas, in the formation of their risk perceptions. The participants of this study work in the biogas sector, either researching, advocating, deliberating, or selling products; thus, they could perceive risks to be less severe than what they may be, agreeing on their interests to support the growth and continuation of the biogas industry.

Since these stakeholders are in general accustomed/familiarized with the technology, they are inclined to lessen the relevance of any potential risks associated with biogas and with PtG. This pattern in risk perception has been described in various studies of risk research (Bostrom, 1997; Krewski et al., 2012; Otway and Winterfeldt, 1992).

The sociocultural and conceptual inclinations of various interest groups have a crucial influence in the formation of their risk perception and their preferred risk management approaches. This is a notion proposed by the Cultural Theory of Risk (CT) (Douglas, 1992; Douglas and Wildavsky, 1983; Lupton, 1999; Rayner, 1992) that can be reflected in various socially regulating aspects, such as accountability, trust and legitimacy. These values affect the arguments on risk, which tend to express the conflicting interests and opinions in society (Nelkin, 1989).

In the CT, individuals select risks based on their guiding principles, viewpoints and the social order they prefer to have, which are subject to a cultural disposition related to their lifestyles and worldviews towards risks (Douglas, 1992). Based on this theory, individuals are studied in terms of their opinions and the roles they identify as ideal in their social context (Mamadouh, 1999).

This attitude among the interviewed stakeholders, of posing strong confidence in ordinances and regulatory institutions to maintain environmental and safety risks under control; and of seeing risk management as a task of governments by setting regulations, is typical of "hierarchists" (Douglas, 1992; Schwarz and Thompson, 1990; Rayner, 1992; Wildavsky and Dake, 1990; Oltedal et al., 2004). Hierarchists are one of the four types of people's attitudes towards risks as depicted in the CT (cf. 2.2.2), favor having highly structured organizations, social specialization and the clear assignation of roles.

They rely on rigorous ordinances and governmental screening to keep impacts, e.g., on nature or operators, within boundaries and to avoid or mitigate potential hazards. Hierarchists also believe that environmental and technological risks are meant to be handled by experts (Douglas, 1992; Hoogstra-Klein et al., 2012; Oltedal et al., 2004; Rayner, 1992; Schwarz and Thompson, 1990; Wildavsky and Dake, 1990).

Other studies provide evidence of cultural factors influencing stakeholders to perceive fewer environmental risks due to their trust in regulations, governmental institutions and the social order in general, to appropriately take control over such risks (Hoogstra-Klein et al., 2012; West et al., 2010; Xue et al., 2014).

All interviewed stakeholders concurred on the need of establishing policies as the central means to handle mentioned risks and challenges in the biogas industry and in association with PtG. However, interviewed participants did not provide concrete components of the mechanisms of such regulations. They see politics as a black box that is dissociated from them and that spontaneously reacts in case of an emergency and inherently knows what must be done. This situation may indicate that a comprehensive understanding of necessary measures beyond establishing regulations to manage risks in the biogas industry appropriately is currently missing among multiple stakeholders of this sector.

This kind of stance towards risks is very problematic in the management of technologies associated with complex, uncertain and ambiguous risks. If such dangers are ignored and not addressed timely and appropriately due to cultural mindsets, serious threats could be underestimated and tragic accidents may occur.

Biogas installations continuously confront accidents and operators remain being accused of mismanagement (cf. 3.1). It is thus necessary to increase the environmental and safety risk awareness among the stakeholders of the German biogas sector, on how to identify and deal with cultural influences in the way they perceive and handle risks linked with this technology and its innovations.

Moreover, it is proper to urge them to consider the concepts of Risk Governance (IRGC, 2017; Renn, 2015; Renn and Klinke, 2015) and the Precautionary Risk Principles (Klinke et al., 2007; Pretty et al., 2007; Renn et al., 2004; Stirling, 2007; Stirling, 2017). These notions include understanding risk identification, assessment, management and communication as an all-encompassing and continuous process of dealing with information and uncertainty in a participatory, legitimate and accountable way.

Furthermore, awareness on the various dimensions that encompass risks is essential for an efficient risk governance, i.e., its social context, traditions on regulatory measures and mechanisms of law enforcement, relationships among multiple stakeholders and prevailing organizational capacity (IRGC, 2017).

Thereby, stakeholders and interest groups in the biogas industry can gain a comprehensive understanding of preventive and participatory risk management concepts. Besides, they become informed about measures and strategies that correspond with the sociocultural context, which they could integrate into their approaches to achieve lasting and effective risk control.

6.2.3 Technology stigmatization and implications for biogas and PtG

Stigmatization of biobased products and biogas

It was evident that interviewed stakeholders in this study believe that biogas has been blamed both by the public and politicians for causing adverse impacts on the environment. Participants of this study perceived this situation as a substantial aspect that challenges the progress of any innovation associated with the biogas sector.

Interviewed stakeholders also agreed that there is a negative attitude in German society in regard to biobased products derived from the biogas value chain. They argued that this rejection was formed due to a stigmatization to biofuels, a related bioenergy field, a sentiment that may be transferred to biogas and its by-products.

On this matter, it could be understood that people may have stigmatized biogas on the base of its dependency on energy plants and mainly maize. Nevertheless, more empirical evidence is necessary to assert if using maize as primary feedstock in the bio-industry has been indeed stigmatized in German society.

The concept of technology stigmatization has been extensively described in previous works (Flynn et al., 2001; Kasperson et al., 2001; Kasperson et al., 1988). Assessing this topic is of high significance since massive economic losses could be reported, capable of eradicating the whole field. Technologies may confront the risk of being marked, e.g., due to pollution or for damaging the ecosystem with monocultures. Ultimately, they could end up being rejected, failing in its market insertion and in the aspiration of obtaining the benefits associated with them, e.g., environmentally friendly biobased products versus conventional ones.

It is important to accentuate that biobased goods are of particular relevance in Germany since they are part of the "Nationale Politikstrategie Bioökonomie" – National Political Strategy in Bioeconomy, which aims at mobilizing a knowledge-based economy and the use renewable sources efficiently, to generate products and services of benefit in the economy (Kainz, 2016). It is therefore vital for decision-makers to be aware of the concept of technology stigmatization, to identify disadvantageous characteristics of biobased products that could be marked, stigmatized and finally disregarded in public.

Sijtsema et al. (2016) explained that people tend to have ambiguous thoughts when confronted with biobased products, leading to uncertainty. Both positive and negative sentiments arise in association with environmental protection in contrast to their impacts. They provided evidence on the limited acquaintance of the public with the concept of a biobased economy.

This aspect of people's little experience with bio-products, together with the opinion of the stakeholders in the present investigation about potential stigmatization of biobased energy and material providers requires attention since the more controversial, intricate and ambiguous a concept is for people, the more plausible it is that they will develop fearfulness against it (Renn and Benighaus, 2013). This situation is ultimately reflected in the refusal of a technology and consequently ignoring its pledged benefits (Flynn et al., 2001; Kasperson et al., 2001; Kasperson et al., 1988).

The role of media in the amplification of risks

The interviewees distinguished the media as an amplifier of previous accidents in biogas installations and remarked it as an essential influencing channel, altering people's opinions. Despite this understanding of the media among the stakeholders, they did not identify it as a crucial instrument in dealing with their perceived risks and challenges of the biogas sector and in association with PtG. They merely referred to the media in the form of blame due to the diffusion of negative information on biogas.

Some stakeholders from associations together with some from science indicated that the news in Germany has "cherry-picked" accidents in biogas, displaying only selected, incomplete and even false information to the public and generalized accidents as if they were happening in the entire sector.

These stakeholders expressed that people may have oversimplified the news they received about accidents in biogas, stigmatizing this way the entire biogas industry. On this matter, stakeholders from politics subtly mentioned that there are still negative headlines about biogas, influencing people's attitudes towards the technology.

Furthermore, it was evident that most of the stakeholders understood communication with the public equivalent to propaganda, which is not analogous. It was noticed that each sector had interests to protect, seeking ways to convince the general public to endorse them. In general, the stakeholders understood that this could be done via what they call "image campaigns"; through which they provide information to the society defending their interest in the biogas sector.

The argumentations of the interviewees in this study, regarding the influence of the media on people's risk perception and technology stigmatization are aligned with the previous described SARF (cf. 2.2.3) (Kasperson et al., 2014; Kasperson et al., 1988; Renn, 2011; Renn et al., 1992).

In this theory, the media has been described as an essential station that intensifies or lessens characteristics of a risk issue, which is then passed on to people, subsequently intensified in the process of risk communication and transfer of information. Consequences of this process are multiple, which may include increased people's fear and distrust in a technology, leading to economic losses for a field and even its downfall (Kasperson et al., 2014; Kasperson et al., 1988; Renn, 2011; Renn et al., 1992).

The role of the media should then be prioritized as a strategic instrument to deal with risk perception and remove any stigmatization of the biogas industry in the general public. The stakeholders should prioritize dealing with their media presence since it could aggravate a process of rejection/stigmatization of a technology, as it is an essential station in a risk amplification process.

Since the media influences people's attitudes and what people may identify as threatening or not with the images and content it provides, decision-makers should contemplate it as a vital mechanism to handle risk perceptions in society and to communicate how risk control measures are implemented, which is different from mere publicity.

By understanding the links between risk amplification and the rejection or stigmatization of a technology, the stakeholders may prevent extreme judgments of the biogas sector and its innovations, thus facilitating its diffusion. Stakeholders should go beyond acknowledging the influence of the media on people's opinion.

Instead of lamenting their unfavorable image in the media, they should strategically use the various means of communication to disclose relevant and credible information on how environmental and safety risks are being handled in the sector, which in turn will benefit the reception of the field and its innovations in the population. Besides, it may help to increase trust and legitimacy in the population and to enable means of communication among all interested sectors.

6.2.4 Alleged knowledge gap in the population

It was common among stakeholders from science, industry and associations that the reason why the public complains about biogas is that they are not knowledgeable about the risks posed by climate change and so do not comprehend the relevance of supporting environmentally friendly technologies. They considered people's judgments and perceptions to be focused on utilitarian factors, seeking to maximize their convenience and focusing on their economic benefits than on the need to combat possible environmental risks.

Stakeholders from science, industry and associations hinted that biogas and PtG are complex topics and that people are still ignorant about the technology in contrast to beliefs from politicians. These stakeholders referred to biogas and its methanation process, which they consider the public has not understood since it was deployed in the early 2000s.

Stakeholders from science believed that only they could identify "real" sources of risks (and not the public or laypeople, as they named them) to provide suggestions on risk management strategies and policies. Like stakeholders from science, those from politics believed that scientists should provide them with reliable information on the state of the art of the technology. However, different from stakeholders from science and industry, stakeholders from politics understood that also social scientists are essential to identify areas of potential societal conflict.

Stakeholders from science recommended informing people and raise awareness about biogas and PtG and their related benefits. This attitude could be shared among participants working in science, industry and associations, trying to simplify people's distrust, criticism and refusal and categorizing it as ignorance in the population.

Among the interviewed stakeholders, regarding people's attitudes towards risks was evident that currently, a comprehensive understanding of how risk perception is formed in society is missing. Besides a cost-benefit analysis, the interviewed participants did not refer to any other of the elements described in the literature that determine an individual's risk perception, e.g., values, worldviews, beliefs and affections, as described in the theories of risk perception (Keller et al., 2006; Nelkin, 1989; Slovic, 1992, 1987; Sobkow et al., 2016). Being aware of the factors that influence people's attitudes towards risks associated with a technology may assist stakeholders of the biogas sector to improve their risk communication and the way they relate with the public.

Multiple stakeholders lessened their responsibility in the whole deterioration of the biogas image in the general public as well as the relevance of people's responses to it. They referred to the public as merely "ignorant", as conventionally believed among experts according to the "Knowledge Gap Theory" (Cohen, 1998; Einsiedel, 2000; Hilgartner, 2016; Irwin and Wynne, 1996). This conservative view, such as stated by stakeholders from science, industry and politics was common in the risk assessment field for a long time, in which a high trust was given to expert knowledge for risk identification and assessment. Under that theory, scientific evaluation of risk had supremacy over laypeople's interpretation of risk.

Previously, differences between experts and laypeople's judgment on risk were explained as a lack of knowledge in the latter (Cohen, 1998; Einsiedel, 2000; Hilgartner, 2016; Irwin and Wynne, 1996). However, various investigations have confronted this notion and found weak indications for its claims (Boholm and Prutzer, 2017; Sjöberg, 2002; Sjöberg, 1999).

When considering risk assessment, two aspects should be taken into account: on the one hand, one has to be aware of evidence provided that experts may be subject to motivation and cultural inclinations (Bostrom, 1997; Kasperson et al., 1988; Krewski et al., 2012; Lynn, 1986; Otway and Winterfeldt, 1992; Rowe and Wright, 2001; Sjöberg, 2002; Skjong and Wentworth, 2001).

On the other hand, experts may use similar mental models as laypeople do, heuristics (cf. 2.3), especially when they are confronted with risks or challenges beyond their field of expertise, usually exhibiting overconfidence on their capability to manage those risks (Johnson, 1993; Lin and Bier, 2008; Sjöberg, 2002; Skjong and Wentworth, 2001).

Moreover, referring to the public as ignorant is an elitist attitude and thoughtless of the stakeholders interviewed in this study since people's risk perception derives from a complex assessment of broadly legitimized aspects in society.

The understanding of risk is a normative construct, which integrates beliefs, preferences and culturally ingrained social rules (Rosa et al., 2015; Sjöberg, 1999); thus, laypeople's risk perception is legitimate. Instead of referring to the public as uninformed, their judgment should be acknowledged and integrated into the complex decision-making process of risk governance (Boholm and Prutzer, 2017; IRGC, 2017; Lundqvist, 2016; Renn, 2015, 2014).

6.2.5 Dealing with distrust among stakeholders

Distrust in the population

Overall, interviewed stakeholders in this study accentuated that people distrust the biogas sector and its proponents regarding the capability of the sector to implement safe and environmentally friendly facilities. Interviewed stakeholders in this study argued that there is still a disapproving opinion around the biogas sector in the country, referring to earlier controversies linked with the biogas industry. Among the reasons mentioned by the interviewees explaining current doubt and refusal sentiments in the population are: the dependence on maize for energy generation and the continuous accidents happening in the field.

Since 2000, the year in which the EEG was implemented in Germany, the renewable energy support framework has been amended on five occasions (Leiren and Reimer, 2018). The constant changes in the energy policy may send a signal to the population and investors about indecisiveness or uncertainty among policy-makers. They may understand the variability in the EEG as a sign of incompetence, incertitude and a loss of control among the institutions and agents supposed to govern technological risks and uncertainties sovereignly.

As long as stakeholders of the biogas industry do not take account of the environmental, societal and safety risks involved in the biogas value chain, people may feel uncertain about the level of control of such risks in the sector. As a consequence, people will distrust its promoters, show skepticism, discontent and may even refute the technology and its innovations, as it is described in theories of risk communication and social interpretation of risks (Nelkin, 1989).

Considering these arguments, not only knowledge about the benefits of biogas and PtG in the energy system should be provided to the public; also, trust in people should be promoted to strengthen technology legitimacy and acceptance. Interest groups in the biogas industry should improve the way they communicate their risk management measures, to reduce the level of uncertainty in people and thus, gain their support. Besides, by tackling stigmas and properly confronting unfavorable communications on the sector, trust can be restored and credibility in the sector can be strengthened, as suggested by Peters et al. (1997).

Luhmann in 1988 and 1989 firstly characterized the term trust and confidence. Since then, trust has been associated with various aspects such as “affections and competence” (Metlay, 1999); “knowledge and expertise, openness and honesty, concern and care” (Peters et al., 1997). Renn and Levine (1991) distinguished “competence, objectivity, fairness, consistency and faith” as essential aspects of trust.

Conversely, distrust or the absence of the previously featured and socially perceived aspects, is a reasonable response of individuals towards a technology and its proponents if they notice that undesirable consequences occur, while the supporters of the technology keep promising benefits and the illusion of its mastery. People in Germany may believe that biogas operators are not in control of the threats imposed by the technology if headlines in the media continue to show accidents happening in biogas installations (cf. 6.2.3 and 3.1). These unfavorable newscasts could be accentuated if misfortunes continue to happen once PtG is adopted in biogas facilities.

It is vital that the stakeholders of the biogas sector seriously consider and handle the critical issue of distrust in the population, which is directly linked with the acceptance or not of the technology.

Siegrist et al. (2005) proposed that trust and confidence have an opposite effect on risk perception concerning emerging technologies. Indicating that the higher the level of trust present in the society, the lower their feelings of fear towards a technology, thus facilitating its reception in people.

In a recent acceptance analysis, representative of the entire German population was reported that only 32% of the people advocate bioenergy for power supply in contrast to other renewable sources like solar and wind technologies, which were preferred by 68% and 61% in public respectively (AEE, 2018).

When asked on their opinions on how to gain acceptance for biogas and PtG, interviewed stakeholders in this study recommended i) to integrate people early enough in any project; and ii) to communicate the benefits of the technology, understood as increasing knowledge on its advantages. Various studies on technology acceptance have suggested similar measures (Ellabban and Abu-Rub, 2016; Köppel et al., 2017; Ponce et al., 2016; Radics et al., 2015; Xenias and Whitmarsh, 2018).

An investigation assessing the possibilities to facilitate social acceptance of PtG in the German state of Baden-Württemberg also suggested to strengthen communication with the society in general and directly affected communities in the deployment of an energy plan and to promote people's participation in the design of PtG projects (Köppel et al., 2017). Thus, transparency has been identified as a key aspect for strengthening trust and reliability in the deployment of a technology in its social context.

The situation that biogas is the least favorite renewable energy source should be confronted by stakeholders in biogas, who need to be aware of the importance of trust as a basis for technology acceptance. The lower the trust in risk controlling institutions, the higher the perceived risks are in society and so, the lower the acceptance of a technology (Boecker and Nocella; Irwin and Wynne, 1996; Siegrist, 1999). Various authors have emphasized on the need of risk managers and communicators to be conscious on the significance of trust in their risk communication strategies (Luhmann, 1980; Rempel and Holmes, 1986; Siegrist and Cvetkovich, 2000).

Society's reaction to risks is connected to the level of reliability they have on the risk management agencies (Slovic et al., 1991). Trust in institutions is directly linked with risk perception in people. If distrust in risk management agencies reigns in the prevailing opinion, people may dispute risks although authorities declare them to be unharmful or to be under control (Aven and Renn, 2010).

Therefore, instead of judging the public as ignorant, these stakeholders should strengthen trust in actors and institutions, which the society perceive as responsible for managing risks in the biogas sector. Reliance is then translated into more risk tolerability in public, an aspect that is broadly explained by Irwin and Wynne (1996).

Distrust among promoters of biogas

In addition to a perceived public distrust in the biogas industry, there is a widespread distrust in politics and politicians among interest groups, promoters and developers of the biogas technology.

Stakeholders from science, industry and some from political groups and associations interviewed in this study showed strong concern that politicians may be under the influence of lobby groups from industries competing with biogas, wanting to divert the public opinion against the biogas sector. On this matter, Sühlsen and Hisschemöller (2014) published that the four largest companies providing electricity in Germany possess a considerable lobby influence in German politics.

Conversely, some stakeholders from associations believed that politicians are instead already predisposed due to the ongoing negative reputation of the biogas industry in the population.

This is a hint on the loss of trust among stakeholders in biogas on the independent action of politicians, seeing them not as the actors that guard all interests of the society, including theirs, but perceiving them as being subject to the influence of certain industrial groups to assure their prevalence and growth in the energy sector.

The response of most of the interviewed stakeholders about a possible influence of lobby groups on the decision-making and the political economy of the domestic energy system shows an emerging distrust in politicians and politics as democratic and impartial means of participation and representation.

Trust is an aspect that needs to be restored and strengthened in the biogas sector. Such beliefs show a discontent among the interviewed stakeholders about the kind of association they perceive to have with political groups in the country in contrast to other industrial sectors.

Theories on risk governance highlight the role of trust in social institutions and their actors as essential elements for building efficient and effective risk control mechanisms (IRGC, 2017; Renn and Benighaus, 2013). For this reason, decision-makers and risk managers in social institutions must consider tackling distrust in politicians among all stakeholders in society, to facilitate reliability and legitimacy of their resolutions.

6.2.6 Experts' role classification in risk management

Sjöberg (1999) proposed a characterization of experts' roles in risk perception and management. That author classifies them into two groups: on the one hand, protectors, who assume the duty of alerting people about risks, unknown or ignored by them; and on the other hand, promoters, who are inclined at taking risks in exchange of the benefits derived from the adoption of a technology.

Promoters question people's fears towards technological risks since they consider them to be less dangerous or prominent; while protectors are puzzled by the little concern people show to guard themselves against risks of harm or catastrophes.

In this study, stakeholders from science and industry agreed in their opinions, exhibiting an optimistic attitude towards PtG in association with biogas. They emphasized aspirations and promised benefits of the technology. These participants acquired the role of promoters of PtG and biogas.

Stakeholders from politics may have uttered more moderate statements in response to their roles as representatives of the whole population and of multiple groups and not only in defense of the interests of biogas producers, assuming a role of protectors (Sjöberg, 1999). In this respect, they exposed the dilemma of promoting technological progress on the one hand and on the other, the consideration of people's concerns in association with biogas. They mentioned sensitive topics for the society, such as land use, hygienization and avoidance of GHG emissions, reflecting this way topics of relevance from diverse societal groups.

Stakeholders from associations (incl. producers and professional groups) advocated biogas and PtG and expressed arguments in defense of their interest groups in the biogas industry, assuming a role of promotors. They expressed their interest in endorsing the elaboration of a business model, including small biogas producers.

In addition, they pointed at the uncertainties that surround this emerging technology of PtG in biogas, which is of relevance for investors in the sector. As stakeholders from science and industry, stakeholders from associations conveyed their interests, representing biogas managers, looking for business alternatives to compensate losses after their present EEG contracts are no longer valid.

It is important to consider the problems subject to assuming roles since professional interests and affiliation could influence the stakeholders' perceptions of the risks and benefits of a technology (Krewski et al., 2012). Moreover, the sociocultural theory of risk indicates that entrepreneurs (in this case, stakeholders from industry) tend to lessen risks in preference of the benefits rooted in a technology and the potential economic gains envisioned with it (Douglas, 1992; Wildavsky and Dake, 1990). This is an aspect that requires consideration when handling technological risks linked to complexity, uncertainty and ambiguity.

6.2.7 Accountable actors to deal with risk governance

Stakeholders that participated in this study mostly identified politicians as main actors responsible for managing risks, uncertainties and challenges that emerge from biogas alone and in connection with PtG. It was common to find among interviewed stakeholders (including those from political organizations) a clear concept on the kind of influence they expect politicians should have in the biogas sector: a provider of financial support to develop and carry out new projects, enact safety policies and support producers with incentives. The case of politicians is relevant to highlight since different from other stakeholders; they were unanimously identified by the interviewees as main responsible to handle risks, uncertainties and challenges of biogas and PtG.

On their part, interviewed stakeholders from political institutions indicated that politicians have a duty in the current issue. However, they perceived themselves (as part of the political sector) to be less accountable to deal with such risks in comparison to how other stakeholders perceive them to be.

Participants from politics mentioned research organizations to be equally accountable to govern risks, uncertainties and challenges of biogas and PtG, as they provide decision makers with information on technologies and their threats. Overall, the stakeholders shared this opinion, considering that the role of scientists in the matter should be related with the identification of "real" risks (cf. 6.2.4), the development of the technology and providing recommendations for policy and management.

Subsequently, stakeholders from politics identified the media, biogas workers and finally associations as accountable actors to deal with prevailing issues of biogas and PtG. This was a perception shared among the interviewed stakeholders, who highlighted the role of biogas producers in dealing with risks, by constructing and managing plants safely and working on improving their image in the public opinion.

In this study, overall the stakeholders recognized themselves to be less accountable in the matter, in comparison to how other actors identified them to be. They perceived themselves as independent actors, non-liable and distant from handling risk events happening in the biogas sector.

The viewpoint of the interviewees on the role of politicians could be explained by the fact that the biogas industry has been historically financed with subsidies framed under the EEG (Daniel-Gromke et al., 2018): following political measures to expand the renewable energy sector and deploying more environmentally friendly energy sources. That experience with the EEG may encourage stakeholders to believe that further political support through subsidies is the appropriate response to deal with what they understand is an essential risk in biogas and its innovation with PtG: the economic uncertainty the sector faces (cf. 5.8).

The identification of political agents as principal actors and regulations/policies as essential means for managing technological risks in the deployment of renewable energies has also been reported in other studies (Gatzert and Kosub, 2016; Karimi and Komendantova, 2017; Komendantova et al., 2012; Popp et al., 2014).

The viewpoint of the interviewed stakeholders on accountable actors to deal with risks is simplistic, partial and does not reflect the core elements embodied in the concepts for a resilient risk governance (cf. 2.1.2).

In the literature, risk governance has been characterized to include not only technical risk management and the contribution of specialists on the epistemological nature of risks, but it also includes among others, risk communication, concern assessment and stakeholder participation (IRGC, 2017).

The response of the stakeholders in this study, perceiving themselves as less accountable for action as others appointed them to be is typical among decision-makers, to abstain from responsibility when dealing with risks, avoiding this way the blame in case of unfavorable consequences (Hood, 2002; Howlett, 2014; Langford, 2011). This attitude can be specially understood in the case of politicians, who may want to evade accountability fearing to be accused of incompetence if adverse events occur.

This situation creates a spiral in which no agent or institution would openly assume duties to manage risks, uncertainties and challenges in the biogas industry. Such response could lead to inaction and may increase the vulnerability of health damages and injuries to operators and pollution to the environment in case of accidents in biogas installations associated with PtG, such as fires and explosions, or by contaminating the environment in case of leaked emissions, e.g., digestate spillage and gas discharges.

The interviewees considered each actor's role as separate and independent from each other. This situation is different from the recommendations for a comprehensive risk governance, in which institutions and its competences, actor networks, regulations and the social climate need to be integrated for a resilient management of risks (Hood et al., 2004; Hutter and Power, 2005; IRGC, 2017; Renn, 2008).

A disarticulated understanding of a social construction of risk and risk governance among the different stakeholders and the exclusion of sociocultural aspects when dealing with risks, could be some of the causes for the current unfavorable situation managing risks in the biogas sector. This is a condition that is mirrored in recurring accidents, ambiguous and controversial opinions towards the sector, reduced acceptance of biogas in contrast with other renewables and a continued lack of trust in the field by the general public.

The engagement of stakeholders for managing risks is an essential aspect for a robust risk governance (IRGC, 2018; Renn, 2014); and for that, the assignation and recognition of roles among the stakeholders are essential.

On this subject, (Renn, 1998a) encourages a participatory decision-making process among various interest groups related to a risk issue, for the identification, assessment and management of risks. It is vital to consider all relevant societal stakeholders not only to express their interests and worries when dealing with technological risks, but also to assign roles in tackling the different facets associated with them. This means, i.e., in the design of technological projects, shaping its social coherence and in the identification and selection of approaches to control possible risks to e.g., the environment, human health, the economy and the social order.

Renn (2015) proposed the cooperative discourse as a methodological approach for a social co-creation of risk assessment (cf. 2.1.2). In this method, stakeholders from different social groups and interests express their apprehensions and understandings of the risk matter and the criteria for evaluating possible management options. In the end, a panel composed of key social actors, e.g., leaders of political, social and cultural organizations, summarize and communicate the findings to the general public. This approach assists in finding a shared understanding, evaluation and management of risks.

Interest groups in the biogas industry should elaborate a comprehensive risk governance as a strategy to not only promote the technology and innovations and emphasize its advantages, but also, to prevent accidents, societal distrust and to deal with its uncertainties and multiple adoption challenges in a cooperative way. The main pillars of risk governance (cf. 2.1.2 & Figure 4) need to be considered in the management of the biogas industry, the adoption of PtG and in the design of future biogas projects.

All relevant interest groups in the biogas sector, including the public, should participate in identifying what are risk issues in association with the sector and in deliberating on required measures for their control. Communication among all stakeholders should be maintained throughout the risk governance process and a monitoring step should assist in evaluating the efficiency of the measures adopted, aiming at obtaining feedback and improving interventions and the management of risks. With this approach, an inclusive and a legitimate control of risks is achieved, leading to more resilient solutions in the biogas industry and its associated technologies.

6.3 Limitations of the study

In this research, the author encountered the following limitations:

- Concerning the distribution of the participants of the study, 10 of the 27 interviewees were located in southern areas of Germany (cf. Figure 21). The data obtained from these stakeholders could have a regional inclination towards the matter. However, the stakeholders were identified in reference to their affiliations, independent of their geographical distribution.
- Due to language constraints, limited time and constrained budget assigned to the study, it was not possible to include the general public and farmers in this investigation. Thus, their risk perceptions were not part of the data analysis of the present research. The viewpoint of representatives from professional groups in which these stakeholders participate, e.g., Fachverband Biogas, were considered in the investigation. This resource joint with desk research provided relevant insights into the operators' risk culture and management.
- The number of participants is not equal from each sector, which may have influenced obtaining more detailed information from a group than from others. The author focused on reaching fullness in the responses of the sample groups, independent of the number of participants consulted throughout the investigation or from individual sectors.
- The sampling method was not meant to be representative of the entire biogas industry. Thus, statements and conclusions cannot be generalized. The author instead aimed at obtaining data saturation from the interviewees that fulfilled the selection criteria (cf. 4.4). Although not generalizable, the results of this investigation provide relevant evidence for understanding current risk management attitude among stakeholders of the biogas sector and on their perception adopting PtG as part of the biogas value chain.
- During the interviews, the stakeholders were not asked to define the term risk. The participant's understandings of the concept were derived from their responses to the questions proposed. Attention was given to the matters in which they explicitly stated as fundamental to protect (of value for them), on aspects on which they were uncertain regarding potential impacts or consequences and when they stated something as challenging for adopting PtG in the sector.

6.4 Outlook for further research

The author recommends the following subjects for future investigations on this matter:

- Since farmers' opinions were indirectly represented in the present investigation through the contribution of specialized associations; the author recommends considering their participation in future studies. In this way, the views of operators of farm-based biogas plants are assessed in contrast to those of the stakeholders who participated in this study.
- In addition to farmers, it was not possible to include the opinion of the public. It is suggested to expand the investigation integrating the public to assess lay people's risk perceptions of PtG in connection with biogas. This way, their perceptions complement the expert risk assessment performed in this study and help identify measures to improve risk communication. Besides, it facilitates a shared understanding of risk and risk governance among the different interest groups.

  This knowledge is beneficial to observe topics of agreements and disagreements among laypeople vs. experts that could lead to societal conflicts. Such a study can also help analyze areas that require special attention for political intervention. Ultimately, this investigation could help draw vital elements for the elaboration of policies that help improve the governance of risks in this field.
- Besides gender (included in this research), other socio-demographic characteristics of the experts were not available, such as age, educational background, religion and social status. These aspects could be of relevance explaining specific risk attitudes of the stakeholders and possible sources of predispositions that may influence their risk judgments.

  An investigation considering characteristics of the participants may assist in testing concepts of the Psychometric Paradigm. Correlations could be obtained that help to understand the relationship between various stakeholders' characteristics in relation to their current risk perceptions and preferred risk management options.

- Studying the applicability of the SARF to further explain the influence of the media and stations on people's risk perception towards biogas and its innovation with PtG. This investigation can be organized to make possible a distinction between multiple sectors and their roles in transmitting information and risk characteristics (stations) and to analyze possible influencers accentuating or lessening risks, e.g., socio-demographical features, level of education, profession, gender, location or age.
- Societal transformations occurring in parallel to PtG and biogas could also be considered in future assessments of risk perception in the German social context. Multiple factors influence people's attitudes that go beyond affections, knowledge or ideologies. Also, sociocultural and political transformations may influence people's views on risks, e.g., migration, increasing inequality and the costs of living, more access to technology and information and growing feelings to search for authenticity.

All these elements could be of relevance to explain people's risk perceptions concerning biogas and its innovations, having the Reflexive Modernization Theory of Risk as a construct of reference. This notion explains risks in relation to challenges faced by contemporaneous societies, dealing with pronouncing individuality, high availability of information and complexity, challenging traditional political schemes and conventional means for risk management (Rosa et al., 2015).

Chapter 7. Conclusions

The findings of this study show that the interviewees described merely technological advances in the adoption of PtG in the biogas value chain and provided little explanation on how this innovation in biogas aims to fits with the social expectations, interests, values and norms of the German society. Interest groups in the biogas industry should consider the social context of this energy notion in order to facilitate the legitimacy and acceptance of the biogas technology and any proposed innovation in the sector.

By understanding socially constructed expectations of a technology, developers of PtG and biogas, risk managers and decision-makers can integrate strategic elements in the design and promotion of this technology in its social background. This way, the cohesion of the technology is facilitated to its public context, aligned with the socially created standards of what is beneficial and how that innovation should be rooted into their shared social systems and beliefs.

The optimistic attitude of stakeholders from science and industry versus a more conservative position of those from politics and associations reflect that the experts in this investigation assumed roles in reference to their judgments towards risks posed by biogas and PtG. Professional motives could have influenced the participants to build either a confident attitude towards the technology, taking the role of promoters, or being cautious in their statements concerned by impacts on people and the environment, as protectors do according to the expert roles theory in risk perception.

The prevailing attitude among the stakeholders who took part in this investigation regarding their expected unenthusiastic market response towards biomethane-based products could be associated with them believing that the public holds a negative imaginary towards sources of energy demanding biomass for their generation.

Besides considering the social context of a technology, the provision of adequate information on the benefits and characteristics of bio-based commodities to the people could facilitate their acceptance in the German market.

There is sound evidence of sociocultural dispositions influencing the risk perception of stakeholders in biogas from science, industry, politics and associations, who took part in this study.

This situation could explain the current risk management within this field. Interviewed stakeholders revealed high reliance on regulations as single means to avoid and control risks and challenges associated with biogas and its innovation through PtG. This attitude towards risks is typical of hierarchists as described in the Cultural Theory of Risk.

The mindset of the interviewed stakeholders, exhibiting a high-risk tolerance towards biogas and PtG, may be associated with motivational and cognitive inclinations. Such attitude could be present in these actors in defense of their professional interests and due to their high familiarity with the technology; leaning on experience and know-how as means to circumvent risks and building a sense of control on any threat or challenge associated with the technology and the sector.

The participants of this study perceived instead as a substantial risk to the progress of any innovation associated with the biogas sector, that the field has been blamed for causing negative impacts in the environment. They believed that both the public and politicians, whom they perceived to be influenced by lobby groups, have defamed the biogas industry.

It is vital for decision-makers and interest groups in biogas to be aware of the concept of technology stigmatization, to identify disadvantageous characteristics of the biogas technology and of biobased products that could be marked and finally rejected in the public. Consequences of this process are multiple, which may include increased people's fears and distrust in a technology, its promoters and risk regulating institutions, leading to economic losses for a field and even its complete downfall.

Multiple stakeholders in this study lessened the relevance of people's attitudes towards biogas. They commonly referred to the public as merely "ignorant", incapable of understanding the complex concept of biogas and PtG. The understanding of risk is a normative construct, which integrates beliefs, preferences and culturally ingrained social rules.

Thus, laypeople's risk perception is legitimate, and their involvement and judgment should be considered in the complex decision-making process of risk governance. Instead of judging the public as ignorant, stakeholders of the biogas industry should strengthen trust in risk managing actors and institutions within society, which is then translated in more risk tolerability (confidence) in the public.

Moreover, being aware of the factors that influence people's attitudes towards risks associated with a technology may assist stakeholders of the biogas sector to improve their risk communication and the way they relate with the public. As long as stakeholders of the biogas industry do not take account of the environmental, societal and safety risks involved in the biogas value chain, people may feel uncertain about the level of control of such risks in the sector and its associated technologies. As a consequence, people will distrust its promoters, show skepticism, discontent and may even refute the field and its innovations

The author recommends the stakeholders of the biogas industry to purposefully consider the media as a suitable instrument to empathize with the public and to provide them with accurate information on how society's perceived risks are being handled in their industry. In doing so, trust in the biogas industry can be strengthened in the population, which ultimately facilitates the diffusion and support of PtG as an innovation in the biogas sector.

The stakeholders hinted that in a biogas and PtG scenario, producers may still require energy plants to make the biomethane production feasible. If biogas continues needing energy plants linked to a PtG concept, certain sustainability boundaries would need to be set, to avoid adverse environmental impacts, as reported and severely criticized in the past.

The various technological challenges discussed by the stakeholders in this study demonstrate incertitude among the participants concerning this emerging technology in biogas. This situation could be translated into a flight of potential investors if these issues are not adequately solved in a reasonable timeframe.

Regarding actors identified to manage environmental, sociopolitical and techno-economic risks and implementation challenges of PtG in biogas, politicians and politics were perceived as means and barriers for the development of this energy concept. Overall, the stakeholders see themselves less accountable for managing risks than how they perceived others to be. This predisposition makes them shift duties and liability to other stakeholders, particularly, to politicians.

Such attitude of not attributing and recognizing roles and responsibilities for managing risks in the biogas industry and by relying entirely on ordinances as the primary mechanism to deal with risks may lead to accidents, mismanagement and ultimately to a general discontent in the public, as experienced before in this sector. This situation may aggravate negative consequences if uncertainties are not acknowledged, studied and tackled.

A disarticulated understanding of a social construction of risk and of the core elements of risk governance among the different stakeholders could be some of the causes for the current unfavorable situation managing risks in the biogas sector. This is a condition that is mirrored in recurring accidents, ambiguous and controversial opinions towards the sector, reduced acceptance of biogas in contrast with other renewable energy sources and in a continued lack of trust in the field by the general public. The proposed cooperative discourse of Renn (2015) can be a practical approach for a social co-creation and risk assessment that could be adopted in this field.

To deal with this status quo, of a dysfunctional risk management in the biogas sector, the author proposes to increase awareness on risk governance, the influence of risk perception in technology acceptance, risk management and on the precautionary risk concept among stakeholders of the biogas sector. These notions may assist them in dealing with risks in a comprehensive, cautious efficient and effective manner.

Interest groups in biogas should elaborate an all-inclusive risk governance, as a strategy to not only promote the technology and emphasize its advantages, but also to prevent accidents, societal distrust and to deal with its uncertainties and multiple adoption challenges in a cooperative, participatory and socially consistent way. The main pillars of risk governance need to be considered in the management of the biogas industry, the adoption of PtG and in the design of future biogas projects. All relevant interest groups in this sector, including the public, should participate identifying what risk issues are in association with the sector and in deliberating on required measures for their control.

The present study provides knowledge on how culture and the risk perception of experts in biogas are of relevance when managing and communicating risks and when dealing with technological innovations. In general terms, this investigation provides valuable insights regarding sociocultural aspects influencing the process of technology management in the biogas sector. These findings are of interest to researchers investigating the potential of implementing PtG in Germany and particularly to scholars investigating technological risk perception. The aspects discussed in this study concerning the governance and the viewpoints of multiple stakeholders toward technological risks are crucial factors for an effective and efficient implementation of PtG in the biogas sector. Besides, they are useful for the characterization of required measures in the diffusion, acceptance and legitimation of biogas and PtG in the German social context.

The sampling method followed in this study does not allow for generalizations of the findings. However, the results obtained in this investigation provide useful guidance on the current risk perception and management among various interest groups associated with the German biogas sector. Owing to language barriers, farmers did not take part in this study. Besides, bounded to a restricted budget and abridged project-timeline, it was not possible to extend the risk assessment to the general public.

The author recommends expanding the research on risk governance requirements of biogas and PtG to include the opinion of the public and farmers. The contributions of these stakeholders complement the results of this investigation, providing wide-ranging suggestions to risk managers and communicators dealing with the biogas sector and its technological innovations, especially in consideration of locally legitimating aspects.

Moreover, it is recommended in future studies to consider further socio-demographic characteristics of the stakeholders, such as age, educational background, religion and social status. These attributes can help explaining specific risk judgments among the stakeholders and possible sources of predispositions that may influence their risk attitudes.

Another element of interest to ponder for further research is the assessment of societal transformations occurring in parallel to the development of PtG in the German context, e.g., more access to technology and information, increased feelings of authenticity and independence, migration, increasing inequality and costs of living. These aspects could influence the way stakeholders perceive and deal with technological risks.

Finally, it is suggested to study the influence of different social stations amplifying and attenuating risk information in reference to biogas and PtG. Such investigation can help understand the way various social actors and means of communication affect the transmission of risk information and characteristics in society, linked to biogas and PtG and to empirically identify the consequences for the biogas industry and its implications in the renewable energy sector of a social amplification of risks.

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Appendix

Interview Guide

Section I: Drivers and barriers of adopting power-to-gas (PtG) in the biogas sector

1. In your opinion, what are the benefits of this innovation as part of the biogas industry in comparison with other uses of excess renewable electricity?
2. With which other concepts (as part of the biogas production scheme) could biological methanation (BM) as a PtG concept compete to generate CH_4 flexibly?
3. What type of measures would you expect for safe installation and management of PtG within traditional biogas plants?
4. Which risks and challenges do you think may restrict the implementation of PtG on in the biogas sector?

   Please, consider the following domains:

Investment costs	Environmental impacts	Political issues
Societal perception	Technology performance	Competing uses: excess electricity/H_2

5. How could these risks be addressed and who should be responsible for managing them? Which political measures would be necessary?

Section II: PtG in the biogas value chain

6. In your opinion, how could PtG transform the current biogas value chain?
7. How could this technology be competitive as part of the biogas sector based on manure and biowaste as input substrate?
8. What is your assessment: do you think this innovation as part of the biogas value chain could harm the environment directly or indirectly? What can we expect?
9. What is your opinion: are the required political conditions available to build a biorefinery concept based on biomethane (CH_4) from biogas plants? If not, what would be needed?

10. How feasible is the use of CH_4 as a platform substance in the chemical industry?
11. How do you expect the public will perceive the use of CH_4 for the generation of chemical products?

Section III: Energy policy and PtG

12. Which role can PtG play in the German energy transition and the political strategy to reduce greenhouse gas emissions?
13. What is your assessment: Do you think there is a link between the public opinion and the political support for the biogas sector?
14. How could PtG be promoted to biogas producers and the public?
15. What kind of incentives could make the biogas industry and its various by-products more competitive?

Curriculum Vitae

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07/2016 – 01/2018	Stay Foundation, Germany Project Coordinator for Acquisition of Grants (pro bono)
03/2014 – 01/ 2018	University of Hohenheim, Germany Research Assistant & Project Coordinator
Education	
11/2014 – present	University of Hohenheim, Germany Doctoral candidate in Agricultural Sciences (Dr. sc. agr.) Research Grant of the Ministry of Science and the Arts (MWK)
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09/2002 – 09/2006	Instituto Politécnico Loyola, Dominican Republic Technical high school, specialized in Agronomy University entrance qualification
09/1994 – 06/2002	Escuela Parroquial Santa Rita, Dominican Republic Elementary and middle school
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Publications

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