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Changing risks in existing gas infrastructure in the Netherlands: are traditional hazard analysis methods equipped for an energy transition?

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ABSTRACT

Countries with extensive gas infrastructures are increasingly turning towards gasses that are produced from renewable energy sources, such as biomass, solar and wind. While these renewable gasses such as biogas/green gas and possibly hydrogen are compatible with existing infrastructure, they exhibit different combustion and explosion behavior. Current safety practices designed for natural gas are not sufficient to ensure a similar level of safety, and must be updated to mitigate changing risks. Additionally, new actors are emerging who are involved with the production and distribution process. The current paper analyzes the extent to which the gas sector in the Netherlands is equipped to deal with a changing risk profile by elaborating on two risk analysis methods. These methods are applied to a segment of the green gas. We find that the Bowtie method that is currently used in the sector provides an understanding of the physical and technical aspects of risks related to green gas provision and is instrumental in communicating them to a general audience. It is also, however, largely static and does nog accommodate changing technical and institutional features of gas provision. The System-Theoretic Accident Model and Processes (STAMP) model, conversely, provides better tools to understand the interaction between incumbent and new actors and technology in the gas sector and provides comprehensive design recommendations for renewable gas systems to a specific audience.

Keywords: STAMP; Bowtie; Renewable Gas; Energy Transition; Safety

1. INTRODUCTION

The transition towards renewable energy sources gives rise to a variety of safety concerns in the Dutch gas infrastructure. Natural gas is increasingly substituted by renewable gasses to curb CO_2 emissions, limit global warming and make up for dwindling domestic natural gas resources. While these renewable gasses can be transported through existing natural gas infrastructure, they exhibit different combustion and explosion behavior compared to natural gas. As is the case for natural gas, the major safety hazard related to renewable gasses is leakage. Across the whole of the gas system, leakage can lead to a wide range of accidents: it can result in poisoning, explosion or fire inside dwellings or outdoors. Yet, the risks posed by renewable gasses—while these include hydrogen and synthetic gasses, we limit these to biogas in the current paper—change and their transport and combustion may also give rise to new hazards. For example, the relative high density of biogas (compared to air, but also compared to natural gas) causes explosions to stay low

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above the ground, whereas natural gas explosions shoot up. This may lead to larger damages and requires new or updated mitigation strategies for grid operators and emergency services. However, renewable gasses do not by default pose a higher risk than natural gas. The use of hydrogen, for example, would eliminate the danger of carbon monoxide poisoning because its combustion does not release anything but water, as opposed to the potential carbon monoxide release during natural gas and biogas combustion. In short, actors associated with maintaining safety in and around the gas infrastructure must be prepared for a rapidly changing hazard profile.

Safety in the Dutch gas sector has long been maintained by relatively small group of actors. Traditionally these actors comprised of two large oil and gas companies Shell and Exxon-Mobil to produce and sell natural gas; the Dutch state to orchestrate annual gas production mandates and (high-pressure) infrastructure development; and a variety of municipal and provincial governments that owned local gas (low-pressure) distribution companies. Since the liberalization of the gas sector in the 1990s, gas provision has been strictly separated between commercial and non-commercial activities. Gas production, trade and sales are executed by private parties while the transport of gas is operated by system operators owned by municipalities, provinces and/or the state. Importantly, liberalization facilitated entry to the gas market for new gas producers and granted them access to existing infrastructure. The anticipated growth in renewable gas production is set to increase the number of gas producers and is likely to make gas production more diverse. The production of gas is no longer limited to large oil and gas companies, but increasingly involves actors such as operators of waste treatment plants or farms that produce biogas. As a consequence, existing safety protocols and guidelines must be updated to include changing risks, new hazards *and* more actors involved in (potentially) causing and mitigating these. The current paper investigates if the hazard analyses that are currently in use in the Dutch gas sector can sufficiently address these changing technical and institutional realities.

Hazard analysis in the Dutch gas sector is now primarily done by Bowtie analyses (Coteq Netbeheer 2017; Liander 2015). These analyses are not limited to natural gas, but also actively used to anticipate on hazards associated with biogas and hydrogen (Van Eekelen et al. 2012; KIWA 2018; RVO 2016). Bowtie analyses focus on a central event—the hazard—that may ultimately result in a variety of accidents. Barriers are then identified that can prevent the hazard from happening (the left side of the bowtie), or that can mitigate consequences (the right side) (de Ruijter and Guldenmund 2016). The resulting bowtie gives a visual representation of different hazard scenarios that is easy to understand and popular among academics and practitioners. As industries grow increasingly advanced, however, new hazard analysis methods have been developed that include more (possible) causal factors. Authors propagating these hazard analyses, such as Nancy Leveson and Erik Hollnagel, claim that traditional hazard analyses are ill equipped to analyze safety in industries where increasingly more components interact to a common goal, often assisted by advanced software and cognitively challenging human operator skills (Hollnagel and Goteman 2004; Leveson 2011). Various comparisons between traditional hazard analyses and their newer counterparts have indeed yielded different and complementary results (Chatzimichailidou et al. 2018; Leveson 2016; Merrett et al. 2019). The current article is similar in that it puts forward a comparison between the Bowtie method and Leveson's Systems-Theoretic Accident Model and Processes (STAMP) in order to investigate if the Bowtie method is sufficient in analyzing safety in the rapidly changing Dutch gas system. We test this question by comparing the traditional bowtie analysis as employed in the Dutch gas sector with the new STAMP methodology.

The comparison of both models is focused on the injection of biogas/green gas in the regulated distribution grid. This case reflects the changing reality of gas provision in the Netherlands, as it concerns 1) the production of biogas; 2) the relative small scale of production facilities; and 3) the injection of gasses in the low to medium pressure distribution and not in the centrally controlled high pressure transmission grids. Our findings hold implications for the future development of biogas grids but also for hydrogen and other gasses. The comparison of the two methods yields an extensive list of safety requirements that raise fundamental issues for further research but the theoretical implications reach farther. We link the outcomes of the hazard analyses to specific institutional problems that are left for further research. In the following section, we provide the background of hazard analysis theory and introduce relevant terminology; Section 3 describes the biogas case and explains the use of *green gas*, and analyzes it using both methods; Section 4 compares and analyzes the results, discussing their relevance and possibilities for improvement; Section 5 concludes.

2. HAZARD ANALYSIS THEORY

Several key concepts and words must be clarified before discussing various hazard analyses. The focal point of a hazard analysis, a hazard, is “a set of conditions that may lead to an accident or loss” (Riemersma et al., forthcoming; Leveson, 2013). Hazard analyses aim to identify hazards so as to assist avoiding accidents and losses. The likelihood of accidents and losses happening, combined with their severity—or, in other words, the risk—can be estimated in a consequent risk analysis (Aven 2011; Christensen et al. 2003). Risk is expressed as a number, whereas hazard analysis can also be qualitative. Hazard and risk analyses have at least a century old history, and are developing still[2]. This article discusses two hazard analyses: one that is currently in use in the Dutch gas sector (Bowtie), as well as an alternative (STAMP). We first introduce both methods before applying them in Section 3.

2.1. Bowtie Method

The Bowtie method is a consolidation of several models that were developed over the course of the 1960s and 1970s. It is centered around a critical event and resembles a bowtie as shown in Figure 1. This figure shows how different causes on the left side can initiate the event, after which it can lead to accidents with various consequences; the safety barriers are installed to prevent (left side of the bowtie) the hazard or mitigate (right side) accidents (de Ruijter and Guldenmund 2016; Swuste et al. 2016). Barriers are not limited to the bowtie methodology, and have been used to visualize and understand safety protocols by many

[2] Paul Swüste and colleagues provided an excellent overview in various installments (Swuste et al. 2016, 2018; Swuste, Van Gulijk, and Zwaard 2010)(Swuste et al. 2016, 2018; Swuste, Van Gulijk, and Zwaard 2010)(Swuste et al. 2016, 2018; Swuste, Van Gulijk, and Zwaard 2010)(Swuste et al. 2016, 2018; Swuste, Van Gulijk, and Zwaard 2010)

more scholars (Reason 1990). They help to make safety measures more visible and identify areas that lack sufficient protection (De Dianous and Fievez 2006).

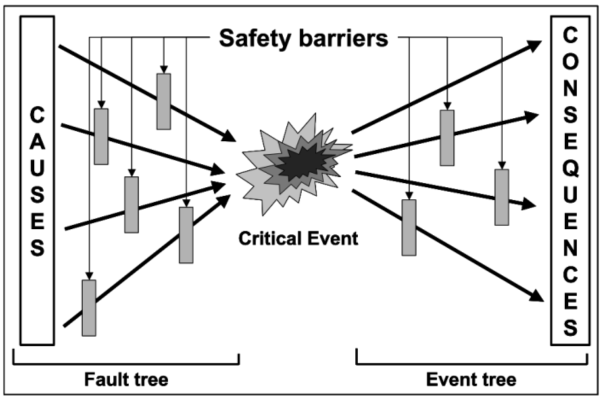

Figure 1. Typical Bowtie analysis (De Dianous and Fievez 2006)

There are a number of varieties of the Bowtie method; the version most common in the gas industry in the Netherlands and also used in this paper was developed by Shell (de Ruijter and Guldenmund 2016). Compared to other variations of the same method, the Shell version is more straightforward and serves to visualize simple cause-effect relationships. Single root causes have a direct line to the central event, and from there can cause any accident outlined on the right hand side (cf. Figure 1). This makes it difficult to analyze how multiple factors can all contribute to an accident. This Shell Bowtie explicitly calls for the level of detail to remain “within reasonable boundaries” so that it remains useful and relevant for its target audience (Visser 1998, 52).

2.2. STAMP Method

There are many methods that provide alternatives to the Bowtie. However, the Bowtie method, as well as other popular hazard analysis methods such as hazard and operability studies (HAZOP) and failure mode and effect analysis (FMEA)[3], have been criticized for not being able to incorporate larger dependencies and more advanced technologies of current systems (Cameron et al. 2017; Dunjó et al. 2010). This section focuses on a hazard analysis tool derived from Nancy Leveson’s System-Theoretic Accident Model and Processes (STAMP) model. This tool, called System-Theoretic Process Analysis (STPA), shifts the focus away from accident or operator failure to including the wider environment in which hazards emerge. The analysis identifies the conditions under which a system is in control, and specifies the requirements that must be met to preserve the safe state. A loss of control—the release of a hazard—results from failure to enforce safety requirements. The STPA approach allows for identification of design errors (either hardware or software) and organizational failures: even if all individual elements of a system work perfectly, STPA can identify hazards that occur from their interaction through poor design.

STAMP is based on systems theory and views a system as interacting *control loops*. These control loops represent the behavior of different system components (human, physical

[3] Also used in the Dutch gas sector, but omitted from this paper.

or social) and function by means of *control actions* executed by *controllers*. The system is interpreted as a hierarchical structure, where each level imposes constraints on the level below it. In other words, control actions enforce safety constraints on lower-level components. The analysis aims to identify the conditions under which control actions become unsafe and, by consequence, can result in a hazard. The control actions are derived from a visual representation of the *control structure*, which represents the functional working of the relevant system. The control structure is accompanied by a *hierarchical structure* that illustrates the elements in the system that exercise control over it. The process will be illustrated by means of a green gas feed-in structure in the next section.

3. Case analysis

Our analysis focuses on hazards related to the provision of biogas in the Netherlands. More specifically, we limit our analysis to the injection of *green gas* into the distribution grid. Biogas refers to all gas produced from biomass but can vary substantially in quality. When biogas is upgraded to match the quality standards of natural gas it is referred to as green gas, and virtually similar to natural gas. Green gas is permitted in existing infrastructure and exhibits the same combustion and explosion behavior as natural gas. It is checked for quality before it enters the grid in order to guarantee compatibility with existing infrastructure and appliances. The inadvertent entry of biogas (i.e. not matching natural gas properties) could jeopardize the integrity of the gas infrastructure in a number of ways. For example, it increases the risk of material deterioration due to aggressive physical properties (i.e. highly corrosive and poisonous hydrogen sulfide); changes explosion behavior so that emergency services are unaware of mitigation strategies; and it emits more toxic gasses upon inadvertent release. The combustion of biogas is also potentially hazardous. Appliances in the Netherlands are attuned to a specific gas quality; departing from these specifications may result in incomplete or faulty combustion, resulting in leakage and risk of poisoning (KIWA 2018; RVO 2016). It is therefore essential to supervise green gas production in order to limit grid entry only to gas that meets the requirements set out in national legislation.

While natural gas and green gas are alike in physical properties, their production methods differ significantly. Natural gas is extracted from domestic resources or imported from abroad on a large scale after which is it is transported at high-pressure (67-80 bars) through a *transmission* system connected to large industrial users and points that connect to lower-pressure (4-8 bars) *distribution* systems. At these points, responsibility for safe transport shifts accordingly from a single national *transmission* system operator (TSO) to any of the seven *distribution* system operators (DSO) located throughout the country. DSOs function as a regional monopoly and have a dedicated service area; they transport the gas onwards to industrial customers attached to the 4-8 bar distribution network until gas eventually reaches small industries and houses through a 100-300 millibar network. Quality control for natural gas is executed by the TSO and takes place at the transfer point between transmission and distribution grid. Hence, DSOs have always been ensured of uniform gas quality in their networks. Unlike natural gas, however, green gas is injected directly into the distribution grid.

The emergence of green gas production created new roles for DSOs. They are responsible for the quality of gas injected into their grid, so they perform checks on the gas that is delivered by green gas producers. While the share of green gas production is still small at 0.3% of the total gas consumption, it is growing rapidly. 2018 saw the total production rise by 11% to 109m³ and the total amount of green gas producers increase from 36 to 43 (Netbeheer Nederland 2019b). In short, the provision of gas—both natural and green—is set to change rapidly. In the next two sections we will analyze hazards associated with green gas feed-in using two methods. The Bowtie analysis (§3.1) is adapted from a variety of Dutch research reports that investigate hazards associated with biogas, green gas and hydrogen. It focuses mostly on the physical properties of biogas, as these are relevant during the process of upgrading to green gas as well as in the case of inadvertent release of biogas into the distribution grid. The STAMP analysis (§3.2) will build on and elaborate the findings of the Bowtie analysis, and add a stronger organizational focus.

3.1. Bowtie Analysis

The Bowtie is currently the most popular hazard analysis method in the Dutch gas sector. Coteq, a DSO that operates in the eastern part of the Netherlands, details their hazard analysis strategy in their yearly report (Coteq Netbeheer 2017). They develop several Bowtie methods in order to visualize risks and safety concerns. The Bowties are periodically updated by assessing new safety concerns, such as those caused by renewable gasses, that are collected through a variety of sources, both internal and external. DSOs collaborate to develop Bowties for gas provision and disseminate relevant information between them.[4] However, DSOs are not the only institutions that make use of this hazard analysis: a report commissioned by the ministry of Economic Affairs also relies on Bowtie methodology to propose guidelines for biogas transport (RVO 2016) and the same holds for an inquiry into the preparedness of Dutch gas networks to renewable gasses (Netbeheer Nederland 2019a).

The analyses quoted above show strong similarities in analyzing hazards associated with renewable gasses. All use established natural gas hazards as a reference point after which hazards associated with biogas or hydrogen are added or modified. The most detailed analysis, concerning biogas hazards, is shown in the appendix and results in a list of barriers summarized in Table 1. Technical consultancy and certification institute KIWA analyzed the hazards associated with hydrogen provision in a similar way (KIWA 2018). They tested the efficiency of barriers in the natural gas bowtie for hydrogen provision, specifying new and changing concerns for safety.

Table 1: Relevant information from Bowtie analysis (summarized from Appendix 1)

Notable barriers (aimed at threat)	Notable barriers (mitigating accident)
Corrosion/deterioration of pipeline due to biogas properties: • Adapt pipeline quality to withstand hazardous biogas properties • Regulate biogas quality so as to limit the amount of hazardous properties • Stop feed-in process when gas leak has occurred **Excavation damage**	**Fire, explosion, suffocation, intoxication in rural areas** • Stop gas flow by facilitating leak recognition (i.e. detectors, gas smell, awareness of emergency contact info) • Incorporate distance of 3.5 meters between biogas pipeline and buildings and check trajectory yearly for changes • Create awareness among emergency

[4] Interview with DSO, may 15th 2019

• Organize required permission for excavation work • Additional preventive measures (i.e. guide excavation activities) **Failing grid connections** • Design leak-proof grid connections **Maintenance works on gas network in operation** • Additional preventive measures (i.e. mark biogas pipelines) • Create more awareness concerning hazards related to biogas	services (i.e. fire fighters, police, ambulance) and update contingency plans to include hazards specific to biogas **Gas Leakage in construction site (leading to intoxication)** • Mitigate damage by removing people from danger zone—wear H2S detecting masks • Incorporate personal protection measures against H2S and moist gas

3.2. STPA Analysis

We limit the STPA analysis to the feeding in of green gas to the grid. This part of the renewable gas infrastructure is especially relevant because it reflects the larger diversity of actors associated with future gas provision.

3.2.1. Accidents to consider, high-level hazards and high-level safety constraints

The STAMP analysis starts by listing accidents that must be avoided. Following STAMP terminology we define an accident as "an undesired or unplanned event that results in a loss, including loss of human life or human injury, property damage, environmental pollution, mission loss etc." (Leveson 2011, 181). A list of accidents to be considered for the transport of biogas was adapted from the Bowties analyzed in the previous section and include:

- A1: Fire/Explosion/Suffocation/Intoxication in rural areas
- A2: Fire/Explosion/Suffocation/Intoxication in urban areas
- A3: Fire/Explosion/Suffocation/Intoxication inside dwellings
- A4: Loss of revenue

As is the case in §3.1, the accidents are all potential results of gas leakage. We specify a number of *high-level safety hazards* at the outset of our analysis with the aim of further specifying them. Similarly, we identify *high-level safety constraints* that are generic safety practices that must be put in place to prevent safety hazards from happening. These high-level safety constraints, too, will be further refined during the analysis. Both are summarized in Table 2.

Table 2: High-level safety hazards and High-level safety constraints

High-level Safety Hazards (HLSH)	High-level Safety Constraints (HLSC)
[HLSH-1] Uncontrolled release on-spec gas from the distribution grid [A-1, A-2] [HLSH-2] Uncontrolled release out-of-spec gas from the distribution grid [A-1, A-2] [HLSH-3] Feeding in of out-of-spec gas into the distribution grid [A-1, A-2, A-3]	[HLSC-1] The hierarchical control structure (HCS) must prevent uncontrolled gas release [HLSH-1, HLSH-2] [HLSC-2] The HCS must respond to an uncontrolled gas release so as to minimize its consequences [HLSH-1, HLSH-2] [HLSC-3] The HCS prevent out-of-spec gas to be fed

[HLSH-4] Interruption of gas supply [A3]	into the distribution grid [HLSH-3] [HLSC-4] The HCS must attend to safely continue gas supply after any possible interruption [HLSH-4]

3.2.2. Control structure, high-level hierarchical structure and safety control actions

Figure 2 (next page) shows the control structure for a feed-in installation of green gas, as well as the authorities surrounding it in the high-level hierarchical structure. All elements of the hierarchical structure exert influence on the control structure by imposing constraints by means of regulation, instructions or certification for example. These constraints can be further specified according to the information derived from the current analysis.

The control structure—within the dotted line—is our focal part of analysis. It illustrates the process where the gas is transported by the *gas producer* from the production plant to the regulated gas grid. The gas producer has equipment to verify if the produced gas meets the quality as specified by the Gas Act; values of Methane (CH4), Hydrogen Sulfide (H2S), Carbon Dioxide (CO2), Oxygen (O) and Nitrogen (N) are checked every 5 minutes. Based on the feedback received from these sensors, the producer can execute two *control actions:* 1) continue gas production or 2) stop gas production. Before the gas is injected into the gas grid, then, the *distribution system operator* provides another quality check in order to independently verify whether or not the gas meets requirements. The information regarding gas quality is received through sensors and sent to a DSO operating center. From there, the DSO can decide remotely whether to 3) feed-in the gas or 4) eject the gas into the air (i.e. flare it).

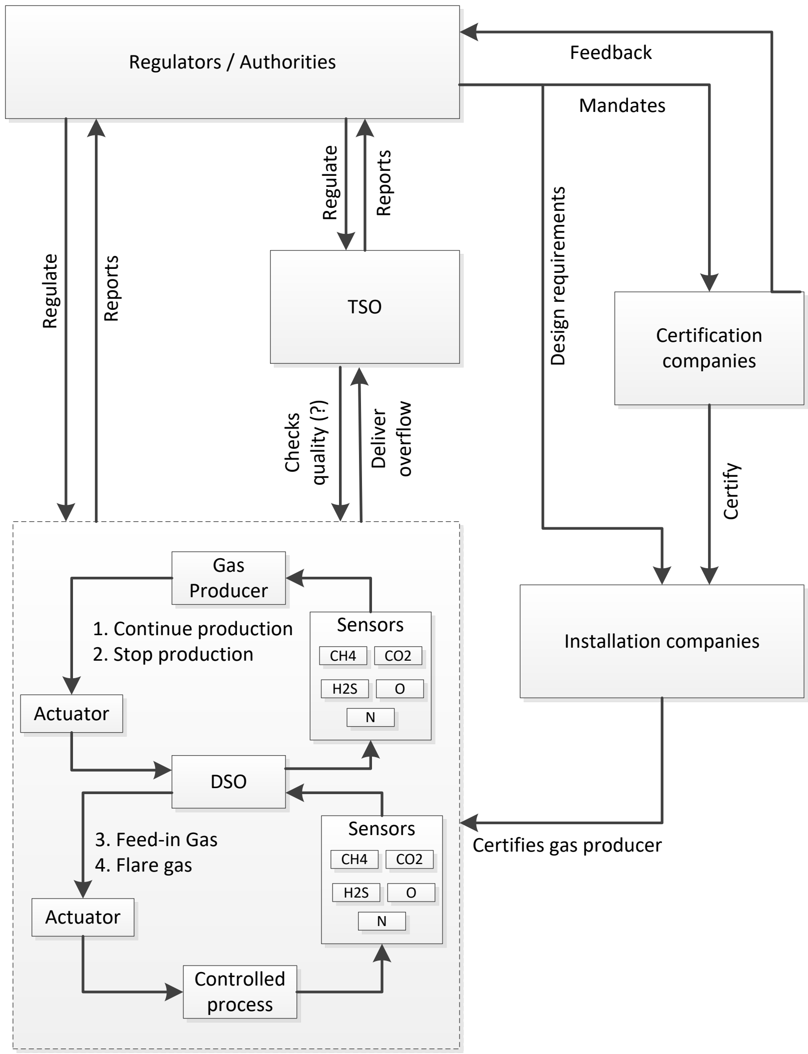

Figure 2: Control structure diagram and high-level hierarchical structure

3.2.3. Potentially unsafe control actions and safety requirements

The previous section identified four control actions. We will now analyze the conditions under which these can become unsafe. Control actions can generally be hazardous in four ways (Leveson 2011):

1. Control action required for safety is not provided or not followed
2. An unsafe control action is provided that leads to a hazard
3. A potentially safe control action is provided too late, too early, or out of sequence
4. A safe control action is stopped too soon or applied too long (for a continuous or non-discrete control action)

For all four identified control actions, we analyze whether any of these four conditions can lead to unsafe behavior. This is summarized in Table 3 for two of the four possible control actions. For our current purposes, we have limited the analyses to control actions 3 and 4. 1 and 2 may follow at a later stage. Control Actions 3 and 4 can yield hazardous situations under 4 specific circumstances—outlined in Table 4 as Unsafe Control Actions (UCAs) 1 through 4. Safety constraints must be designed in order to mitigate these four UCAs; these are also shown in Table 4.

Table 3: identifying unsafe control actions

Control action	Not providing causes hazard	Providing causes hazard	Wrong timing or order causes hazard	Stopped too soon or applied too long
1. Continue production	To Be Determined	TBD	TBD	TBD
2. Stop production	TBD	TBD	TBD	TBD
3. Feed-in gas	Controller does not provide gas feed-in when the gas is on-spec (1)	Controller provides gas feed-in when it is out-of-spec (2)	Controller provides feed-in gas too early when gas is out-of-spec (3)	Controller provides feed-in gas too long when gas is out-of-spec (4) Controller provides feed-in gas too short when gas is on-spec (5)
4. Flare gas	Controller does not provide flaring of gas when gas is out-of-spec (6)	Controller provides flaring of gas when gas is on-spec (7)	Not hazardous	Controller provides flaring of gas too late when gas is out-of-spec (8)

Table 4: Relating unsafe control actions to safety constraints

Unsafe Control Actions (UCA)		Safety constraints (SC)	
UCA-1	Controller does not provide gas feed-in when the gas is on-spec (A4)	**SC-1**	Controller must provide gas feed-in when the gas is on-spec [UCA-1]
UCA-2	Controller provides gas feed-in when it is out-of-spec (A1, A2, A3)	**SC-2**	Controller must not provide gas feed-in when it is out-of-spec [UCA-2]
UCA-3	Controller provides feed-in gas too early when gas is out-of-spec (A1, A2, A3)	**SC-3**	Controller must feed-in gas only if it is on-spec [UCA-3, UCA-4, UCA-5]
UCA-4	Controller provides feed-in gas too long when gas is out-of-spec (A1, A2, A3)	**SC-4**	Controller must provide flaring of gas when gas is out-of-spec [UCA-6]
UCA-5	Controller provides feed-in gas too short when gas is on-spec (A4)	**SC-5**	Controller must not provide flaring when gas is on-spec [UCA-7]
UCA-6	Controller does not provide flaring of gas when gas is out-of-spec (A1, A2, A3)	**SC-6**	Controller must provide flaring only when gas is out-of-spec [UCA-8]
UCA-7	Controller provides flaring of gas when gas is on-spec (A4)		
UCA-8	Controller provides flaring of gas too late when gas is out-of-spec (A1, A2, A3)		

3.2.4. Identifying Loss Scenarios

The identified Unsafe Control Actions and Safety Constraints can be further understood by creating loss scenarios. Creating scenarios possibly enables the identification of more detailed safety constraints and it is also important in identifying how several factors may interact to lead to a hazard. This step, also referred to as STPA Step 2, will be executed for a subsequent version of the current article and is deemed more effective when there is consensus on the appropriate execution of earlier steps (i.e. §3.2.1. – §3.2.3.).

4. ANALYSIS AND DISCUSSION

The two hazard analyses yield significantly different results. The results—summarized in table 5—indicate that the Bowtie yields generic recommendations whereas STPA provides more detailed and in-depth results (i.e. safety constraints*)*. The Bowtie analysis' visual representation allows for a good communication of risk and barriers to a general audience, whereas the STAMP outcomes are better suited for insiders with a high level of specific knowledge. These findings are in line with the purposes of both methods as indicated in Section 2 and also resemble earlier comparisons (Chatzimichailidou et al. 2018; Merrett et al. 2019).

Table 5: Comparison Bowtie and STPA analysis

Bowtie method results	STPA method results
• Regulate biogas quality so as to limit the amount of hazardous properties • Stop feed-in process when gas leak has occurred	• Controller must provide gas feed-in when the gas is on-spec • Controller must not provide gas feed-in when it is out-of-spec • Controller must feed-in gas only if it is on-spec • Controller must provide flaring of gas when gas is out-of-spec • Controller must not provide flaring when gas is on-spec • Controller must provide flaring only when gas is out-of-spec

The wider scope of the STPA analysis allows for a more detailed analysis of complex systems. The results of a more detailed analysis are already visible in Table 5. Unlike the results of the Bowtie methodology, the six Safety Constraints generated from the STPA method pay attention to specific conditions that may contribute to accidents. Not only does STPA generate safety constraints that target physical damage, it is worth noticing that the Safety Constraint [SC-5] targets loss of revenue [A4]—a kind of accident unlikely to be covered in more conventional safety analyses. The STPA method captures more links in the chain leading to possible accidents: where the Bowtie method links action recommendations to a gas leak (i.e. a *hazard*), the STPA method links them to the measurement of gas quality (i.e. a *condition* that may result in a hazardous state when out-of-spec).

The list of Safety Constraints that results from the STPA analysis raises many questions with regards to their preferred implementation. Most immediately, we have not distinguished among the two controllers currently involved with green gas provision: distribution system operators and green gas producers. Both are faced with new roles that must be embedded in existing institutional structures. The governance of these existing structures must be modified to allocate more responsibilities to said actors and facilitate communication and feedback among them, as well as incumbents such as lawmakers, regulators and the transmission system operator. New coordination problems emerge with regards to essential responsibilities for safety governance such as quality control for green gas injected into the transmission grid or the increased involvement of publicly owned DSOs in commercial tasks. These issues must be addressed in further research, but are taken into consideration for future versions of the current paper.

The data for both hazard analyses can be extended by further feedback from relevant actors to arrive at stronger outcomes. The current data has been gathered from interviews with relevant stakeholders over the past two years as well as extensive literature review (Riemersma, Correljé, and Künneke 2019). Further interviews and site visits should be conducted focusing on the interaction between the DSO and green gas producers. These should result in more clearly specified control actions, as well as the conditions under which they are rendered unsafe. Potentially, the analysis could be broadened to include the transmission system operator. It is likely that green gas will eventually be transported through high-pressure transmission grids to balance supply and demand. This would introduce the TSO as a *third* relevant controller, further complicating the distribution of safe control actions. Additionally, safety hazards related to the provisioning of green gas may also resurface for hydrogen and other gasses that will increasingly be transported in the Dutch gas system.

5. CONCLUSION

This paper analyzes the safety of renewable gas systems by applying Bowtie and STPA hazard analysis methods. By focusing on the feeding in of green gas into the distribution grid this paper highlights the way in which both hazard analyses emphasize different aspects of safety. The Bowtie method provides a comprehensive but non-exhaustive overview of changing risks compared to the provision of natural gas. The main outcomes relevant to our case include the regulation of biogas/green gas quality to limit the amount of hazardous properties in the gas and stopping the feed-in process once a leak has occurred. It is striking that the Bowtie analysis includes those risks that were present for natural gas (i.e. regulate gas quality), but fails to mention new risks associated with the provision of green gas (i.e. checking for quality of green gas). While these changing risks can be included into an updated Bowtie rather simply, it does underscore the importance of extending the scope of hazard analysis beyond risks traditionally assumed with natural gas distribution.

The STPA focuses on the detection of gas quality before grid entry and develops strategies to prevent the feed in of gas that does not meet quality requirements. A detailed list of Safety Constraints can assist in shaping institutions that effectively govern safety in future gas systems. We illustrate how the STPA is able to capture hazards that did not surface in existing Bowtie analyses, and argue that the method is superior in identifying and illustrating hazards in an increasingly complex gas system. The visualization of the gas system using control loops situated in a hierarchical system provides a clear overview of the different actors at play, and how they relate to the provision of renewable gas. Especially as the Dutch gas system grows increasingly heterogeneous with more and different controllers, the detailed STPA yields better results than the static Bowtie analysis.

The comparison between the two analyses highlights their different focus. The Bowtie analysis is appropriate for educative purposes among academics and particularly practitioners. Its visualization facilitates an easy understanding of causal relationships between accident causes and accidents as well as offers a good template for identifying and strengthening safety barriers. The STPA analysis is more thorough than the Bowtie and yields more detailed and even new results. It is therefore useful for identifying root causes not (currently) present in the Bowtie analysis and valuable for shaping safety policy for renewable gas provision. These results hold implications not only for green gas or biogas. Keeping within gas provision, many of these findings might hold for the future distribution of hydrogen through existing pipelines or even in independently operated natural gas grids. Beyond the gas sector, these results are relevant for water and electricity provision—traditionally centralized service infrastructures which are increasingly disrupted by new actors operating on a decentralized level.

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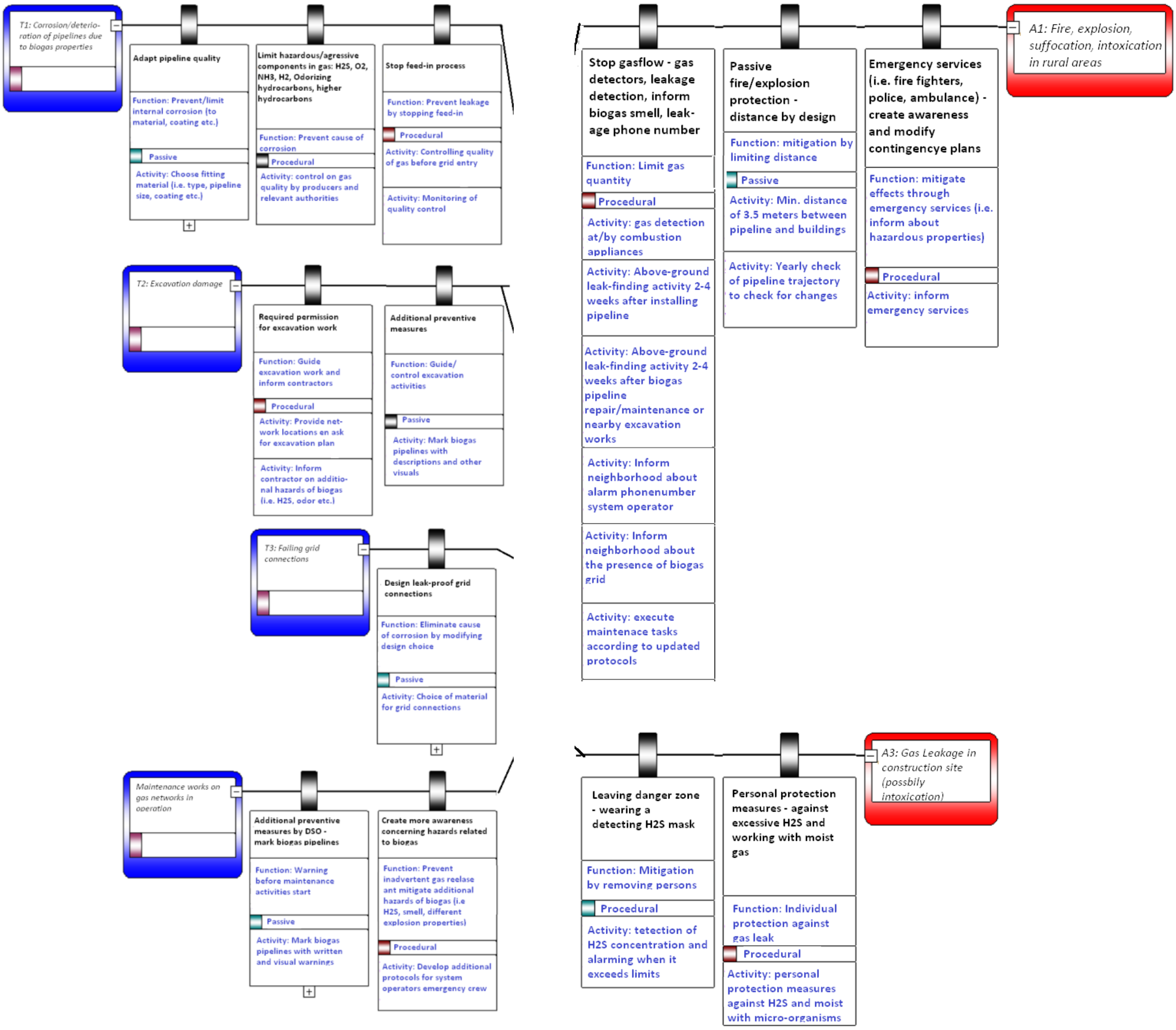
Appendix 1: Edited version of bowtie



Threats and preventive barriers on the left, accidents and mitigating barriers on the right. Edited from (RVO 2016)