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Risk and sustainability analysis of complex hydrogen infrastructures

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ABSTRACT

Building a network of hydrogen refuelling stations is essential to develop the hydrogen economy within transport. Additional, hydrogen is regarded a likely key component to store and convert back excess electrical power to secure future energy supply and to improve the quality of biomass-based fuels. Therefore, future hydrogen supply and distribution chains will have to address several objectives. Such a complexity is a challenge for risk assessment and risk management of these chains because of the increasing interactions. Improved methods are needed to assess the supply chain as a whole. The method of "Functional modelling" is discussed in this paper. It will be shown how it could be a basis for other decision support methods for comprehensive risk and sustainability assessments.

Introduction

Developing a hydrogen refuelling station (HRS) network is the next important step to establish hydrogen as a fuel for vehicles and related services. Such stations will most likely be integrated in existing refuelling stations and result in multifuel storages. These will handle, store and distribute various fuels, as e.g. biomass-based methane, ethanol, gasoline, diesel as well as the traditional crude-oil based products. The power sector regards hydrogen storage as a perspective to secure robust power supply when large shares of fluctuating energy sources replace today's power plants. Therefore, hydrogen supply and distribution chains may likely not only serve to fulfil the demands of refuelling, but also may be important for the wider power and fuel industries. Thus, a future hydrogen infrastructure presumably bridges the infrastructures for transport and power supply.

The operation and control of such complex multifunctional hydrogen supply and distribution networks sets higher demands on the decision-making process addressing the safety and sustainability of these systems. The challenge for risk analysts is to treat many threads in a dynamical system, while most tools to ensure safety are designed to deal with individual plants and their components, see for example [1–4]. Risk assessment that compares different alternative technologies as an input to decision making is a demanding task, even for rather simple cases as a HRS. From a systemic perspective, though, it is essential to take a holistic approach, as system safety is more than just the reliability of its single components.

In order to find the optimal methods and processes, strategic decision making need to compare infrastructures taking

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into account networks of refuelling stations including their supply chains. In a number of European countries such as The Netherlands and Italy it is common to use Quantitative Risk Assessments to find the risk of infrastructures as chemical process plants, tunnels and routes for hazardous-goods transport and to use the outcomes of these to support risk informed land-use planning, e.g. Refs. [5–7].

In a broader perspective risk assessment is part of the general decision support to plan, to design and to establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable. The goal is to have a comprehensive approach, combining and evaluating all considerations in a systemic perspective to find the best solution to ensure the decision support for industries, investors and authorities. Such an approach described by Zachmann et al. [8] may support the development of long termed policies and reduce regulatory uncertainties for the private sector, as regulatory uncertainty is found to be a major barrier in implementing new technologies. By that Zachmann et al. [8, p. 5] recommends to establish a transparent and predictable support policy for all competing technologies and suggests technology choice forecasts using new open multi-technology models that "*should be built, maintained, extended and published by an independent public institution*".

Presently, the scientific literature dealing with the planning and design of hydrogen infrastructures has very limited focus on systems safety. Caputo et al. [9] discuss high safety cost for long-range hydrogen transport through densely populated regions. Kim and Moon [10] predicted the safety costs for an optimized Korean infrastructure partly based on renewable energies. Dayhim et al. [11] implemented risk costs into a multi-period optimization model with the objective function "minimization of the total daily social cost" of a hydrogen supply chain network. Other authors address (e.g. Refs. [12–14]) topics such as the potential growth of supply chain networks, optimization of the investment and running costs. The environmental impacts based on single impact parameters are calculated, as e.g. the carbon dioxide reduction potentials calculated from energy models. Stephens-Romero et al. [15] performed a case study on the optimal implementation of a HRS network using their Spatially and Temporally Resolved Energy and Environment Tool (STREET). The objective was to show optimized investments for HRS networks, while fulfilling e.g. the environmental standards for California. In some papers, the authors take a more technical approach on modelling the system processes and their related impacts, e.g. Ref. [16]. Here, the focus is on component relations and technical comparisons integrating e.g. fuel transport and energy distribution networks. A study on the development of a possible future supply chain [17] optimizing on the fuel price finds that conversion of fossil fuels into hydrogen may be the main driver, while hydrogen production by electrolysis is negligible. While such a result may be expected using a cost benefit point of view, it certainly conflicts with the goal to design for more sustainable solutions. Therefore, a more comprehensive decision support would be a better approach to plan the new infrastructures.

One challenge applying a more comprehensive approach is the handling of the large amount of data and assumptions in a transparent and comprehensive way. At the same time it is important to address the aleatory and epistemic uncertainties that are unavoidable in such studies and to show the influence of new improved knowledge may have on the outcome of a QRA [18–20].

To better cope with the above-mentioned challenges and the uncertainties involved, the following questions raise: How could such a solution be structured? How can one ensure that the various studies that feed into strategic decisions, such as risk assessment, environmental assessment and economic assessment actually deal with exactly the same system? How to compare and decide on the use of alternative technologies in a consistent way? These issues are very complex and, therefore, they need a broad discussion and further development of tools. This paper presents one possible methodology that could help to structure the risk assessment process.

Based on an integrated hydrogen supply and distribution network, the application of the method of "Functional modelling" is presented to show a framework for describing the coupling of functions in a complex hydrogen supply and distribution network, where interferences and strong connections can be found between power storage for electricity supply and supplying hydrogen for transportation. The method "Functional modelling" is described together with a few other decision support tools as Life Cycle Assessment (LCA) and Geographic Information Systems (GIS). The goal is to facilitate the finding of optimal solutions for the development of the infrastructure on a regional or national level. It will be discussed how "Functional models" could support coherent risk and sustainability (Risk Analysis, Life Cycle Assessment/Life Cycle Costing) assessments. By using functional decomposition it is possible at a high level (which means from an early design stage onward) to compare alternative solutions for performing the necessary system functions with respect to safety, reliability, environmental impact, and costs.

The supply chain

Hydrogen is not an energy source in itself and has to be produced from e.g. natural gas using steam reforming or water using large-scale electrolyser and windmill power, as indicated in Fig. 1.

From the production site, the hydrogen may be transported by different means, as pipelines, trucks and/or ships to regional and local storage facilities. The latter ones may be placed directly at the HRS or industrial/domestic sites. The supply chain needs to have storages of different size to store the various amounts of hydrogen on regional or local scale for later use, such as small and large-scale pressurized storage or cryogenic storages.

Methodology

In the following the method of Functional modelling [21,22] is described using the example of the hydrogen supply and distribution chain presented in Fig. 1. The modelling may be followed by performing a high level risk analysis using the concept hazard analysis concept [22,23], which is described in