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The design challenges of replacing natural gas by hydrogen gas in the provision of gas to the Dutch built environment

COSEM Master Thesis – Scientific Article

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Abstract — The Dutch government decided to phase out the natural gas consumption in the provision of heat to the residential and service sector by 2050. The latter policy needs to address the European climate policy to reduce the CO_2 emissions as stated in the Paris agreements. Phasing out natural gas would mean that the comprehensive and costly natural gas infrastructure in the Netherlands needs to adopt a sustainable alternative to natural gas to maintain its function. Hydrogen gas is an alternative gas with the potential to sustainably replace natural gas in the existing gas infrastructure. The effects of a replacement of natural gas by hydrogen gas on the technical and market functioning of the gas infrastructure are unsure. This paper aims to identify the design challenges for the replacement of natural gas by hydrogen gas in the provision of gas to the Dutch residential and service sector. To include both the technical operations and market functioning in the analysis towards the design challenges of a natural gas replacement, a socio-technical system approach is taken. Main design challenges are in the need to develop a new gas production segment with new gas quality standards and a market design that addresses the inexistence of adequate hydrogen supply and demand. Laws and regulations regarding the provision of hydrogen through the public gas grids and the interaction with other energy systems in terms of the technical systems and the market need to be defined. The hydrogen supply will be dependent on the hydrogen production technologies that can emerge under various conditions at various locations. Besides, the energy buffer capacity in the gas system needs to be organized with respect to the total energy buffer capacity in the Netherlands when hydrogen replaces natural gas. The design challenges of the replacement of natural gas are mainly dependent on the political direction of how to develop a hydrogen infrastructure. The future role of a hydrogen provision in the Dutch residential and service sector is hence highly dependent on the political choices that will be made regarding the design of our future energy systems.

Keywords — Hydrogen, Comprehensive design of energy infrastructures, socio-technical systems, replacement of natural gas, Dutch heat provision

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1. Introduction

The Dutch climate policy regarding the residential sector and the service sector states that all buildings need to be provided by an alternative to natural gas in the provision of heat by 2050 (Klimaatberaad, 2018). The heat provision to the residential and service sector is currently for more than ninety percent based on the combustion of natural gas (Hans Ariëns, 2018). The natural gas infrastructure will no longer be needed for the provision of energy to the residential and service sector when the natural gas connections of these buildings are replaced by other alternatives than gas, such as all-electric or district heating. The latter implies that the comprehensive and costly natural gas distribution infrastructure will not be used anymore to provide the annual demand of approximately 700 PJ of natural gas to the Dutch distribution grids (Centraal Bureau voor Statistiek, 2018a). The total annual demand of the electricity sector is approximately 430 PJ (Centraal Bureau voor Statistiek, 2018b). A sustainable alternative gas, such as hydrogen gas, can be used in the existing infrastructure to safeguard the existence of its energy transport and buffer capacity. The latter implies that hydrogen gas needs to be produced, transported, stored, and consumed within the constraints of the current natural gas infrastructure design and operations. The provision of hydrogen gas through the existing natural gas networks can be problematic due to the different properties of hydrogen gas. The current gas infrastructure design and operations need to be adjusted to deal with the new hydrogen gas requirements.

The relationship between institutions and technology in the design practices regarding energy infrastructures is often not adequately addressed. Economists, legal experts, and policy makers focus on market designs that need to address "potential market failures and imperfections, opportunistic behavior, and social objectives" (Scholten & Künneke, 2016, p. 1). Engineers on the other hand, focus on the design of the technical infrastructure assets, network topologies, and control systems that need to function reliably and robustly (Scholten & Künneke, 2016). The fragmentation in the execution of these distinctive design practices can be problematic when design choices of economists, legal experts, and policy makers are not considering the design choices of engineers (and vice versa). This fragmentation can have undesired and unanticipated effects on the functioning of the natural gas infrastructure when hydrogen is utilized. The market design and the technical infrastructure design hence need to be complementary with the new requirements of hydrogen gas and whit each other. To investigate potential design challenges for the market design, the technical system design, and their interrelation, it is important that both design perspectives are included in the conceptualization of the natural gas infrastructure. The research question that will be central in this paper is:

'What are the design challenges for the Dutch gas infrastructure design and operations when natural gas is replaced by hydrogen gas in the provision of gas to the residential and service sector?'

This paper hence focusses on the design challenges that are caused by the applicability of the natural gas infrastructure design to utilize hydrogen gas instead of natural gas. To include both the technical and market design perspectives in the conceptualization of the natural gas infrastructure, a socio-technical system perspective on energy infrastructures is adopted.

The paper is structured as follows. Section 2 will elaborate on energy infrastructures in the perspective of socio-technical systems. Section 3 presents the research methodology. Section 4 discusses the results. Section 5 presents a discussion and the possibilities for future research, and section 5 concludes and presents several policy recommendations.

2. Energy infrastructures as social technical systems

The early work on socio-technical systems is mainly based on the research in the field of large technical systems (LTS). This body of knowledge is considerably initiated by Hughes' (1983) work on the development of large technical systems in the power sector. Other than most research back then, Hughes included not only the technical but also the societal and cultural contexts of systems. Hughes (1983, p.481) identified that power systems encompass both "a technical core of components as well as institutional components" and that "Such encompassing systems should be labeled as socio-technical systems rather than technological systems". The relevance of both the technical and institutional dimensions of energy systems is therewith recognized early on by Hughes. Large technical systems were studied by many scholars from different disciplines with different technical systems as the object of study (Ewertsson & Ingelstam, 2005). In these studies, consensus existed about the importance of both the social and technical dimension of the overall system (Ewertsson & Ingelstam, 2005). It is conceived that Large technical systems are structured around a technical core of physical artifacts that are embedded in, sustained by, and interact with comprehensive socio-historical contexts (Ewertsson & Ingelstam, 2005; Hughes, 1983). The latter is fundamental and suggest that the technological dimension of socio-technical systems is shaped by its interaction with the society where it is created, adapted and developed (Ewertsson & Ingelstam, 2005).

More recent literature on socio-technical theory is focused on the interaction between the social and technical dimensions of systems and the understanding of how they should be designed to function well together. Socio-technical theory is basically founded in two main principles. First, the interaction between the social and technical elements of a system determines the successful performance of a system (Walker, Stanton, Salmon, & Jenkins, 2008). Second, the single optimization of either the social elements or the technical elements tend to increase the unpredictable, non-linear outcome of the system (Walker et al., 2008). The complex non-linear behavior of an energy system, as a result of the interaction of its social and technological elements, is hard to capture (Walker et al., 2008). Socio-technical theory is about the understanding and conceptualization of this complexity. The joint optimization of the social and technical elements of a system is hence an important part in socio-technical systems research. Complex socio-technical systems are defined as "ensembles of technical artifacts embedded in society, connected with natural ecosystems, functioning within regulatory frameworks and markets, and exhibiting a high degree of complexity and dynamics that are not fully understood" (Siddiqi & Collins, 2017, p.7).

Energy infrastructures are conceived to be socio-technical systems with strongly interwoven technical and institutional elements that need a comprehensive approach in analysis and design (Bruijn & Herder, 2009; Chappin & van der Lei, 2014; Crettenand & Finger, 2013; Houwing, Heijnen, & Bouwmans, 2006; Künneke, Groenewegen, & Ménard, 2010; Van der Lei, Bekebrede, & Nikolic, 2010). In energy infrastructures, "performance is about how institutions and technical options incentivize actors and shape activities in the commodity and monetary flows" (Scholten & Künneke, 2016, p. 3). The commodity flow refers to the physical assets and artifacts that function together as a supply chain, as well as their accompanying operational activities in order to coordinate and control the physical flow of energy (Scholten & Künneke, 2016). The existing technology sets the boundaries for what is technically and operationally feasible (Scholten & Künneke, 2016). The monetary flow relates to the transactions that occur in the energy markets (Scholten & Künneke, 2016). The formal and informal institutions structure the transactions within the market. The institutional design and the technological design determine how actors engage in transactions and technical operational activities and therewith how actors behave within the monetary and commodity flow of an energy infrastructure (Scholten & Künneke, 2016).

In analyzing energy infrastructures, it is thus important to notion that the social network and the physical network are interconnected and that they influence each other's development (Herder, Bouwmans, Dijkema, Stikkelman, & Weijnen, 2008). The behavior of an energy infrastructure from a system perspective, is only poorly understood by analyzing the structure and the behavior of the social or technical network in isolation (Herder et al., 2008). Besides the dimension-specific complexity, the interrelation between the social and technical elements of an energy infrastructure adds another domain of complexity to the analysis of energy infrastructures (Herder et al., 2008). This domain of complexity raises the need for a conceptualization of energy infrastructures that considers all the social, technical and economic elements of the system together. Such a comprehensive conceptualization is needed to capture the complexity of the interactions between the social, economic and technical networks of the infrastructure.

Scholten & Künneke (2016) propose a comprehensive design framework that addresses the gap between the engineering and economic perspectives of energy infrastructure design. The framework provides the means to link the design variables of both design perspectives to each other along their various layers of abstraction. Figure 1 illustrates the comprehensive design framework. The purpose of the comprehensive design framework is defined by Scholten & Künneke (2016, p. 16) as the process of "attuning system and market design efforts so that we may better identify, interpret, and address, the interrelated operational and market challenges to energy infrastructure performance." The application of the framework is based on its ability to investigate the implications of a techno-operational or economic-institutional change in a structured manner (Scholten & Künneke, 2016). The framework provides a tool for the positioning of these implications in an easy to use comprehensive overview (Scholten & Künneke, 2016).

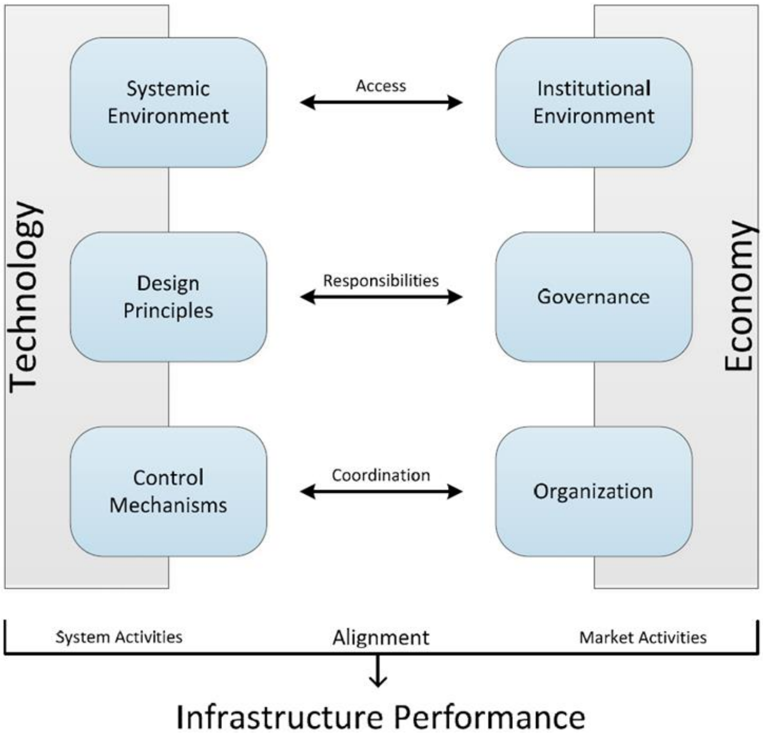

Figure 1: Comprehensive design Framework, adopted from Scholten & Künneke (2016, p. 14)

The three layers of abstraction in the comprehensive design framework refer to the generic design of energy infrastructures (i.e. Access layer), the specific design of energy infrastructures (i.e. Responsibilities layer), and to the coordination of the interactions between the different actors in energy infrastructures (i.e. Coordination layer) (Scholten & Künneke, 2016). In the Access layer, the technical design perspectives of the natural gas infrastructure are linked to the formal institutions that are active (Scholten & Künneke, 2016). The responsibilities layer relates the technical design principles to the governance arrangements. The coordination layer links the technical control mechanisms, that control the technical operational activities, with the modes of organization that structure the market transactions (Scholten & Künneke, 2016). Alignment between these layers refers to the notion that the design choices in the technical dimension cannot obstruct the functioning of the economic dimension (and vice versa) (Scholten & Künneke, 2016).

3. Methodology

The research methodology is based on the application of the comprehensive design framework of Scholten & Künneke (2016). The framework allows for the delineation of both the technical and economic-institutional design of the natural gas infrastructure within the concepts of energy systems as socio-technical systems. It hence provides a tool for the structured mapping of the changes posed by the integration of hydrogen, the design challenges that an integration causes, and the identification of the consistency between the identified challenges. Based on the formulated applications steps for the comprehensive design framework by Scholten & Künneke (2016, p. 17), the following applications steps are formulated:

1. The application of the framework starts with a description of the Dutch natural gas infrastructure. This implies a detailed analysis on the systemic and institutional environment, the relevant performance criteria of the system, the current technologies and operational practices (i.e. design principles and control mechanisms), and the natural gas-specific governance and modes of organization.
2. The second step of the application is to identify hydrogen infrastructure options that are feasible to be integrated in the Dutch natural gas infrastructure. Once identified, these options will be analyzed in terms of the technologies and operational characteristics that they imply.

3. The third step of the application is to investigate what changes in the natural gas infrastructure design because of the integration of hydrogen. This step will be conducted by identifying the elements in the natural gas infrastructure design that need to be added, replaced or adjusted because of the integration of hydrogen.
4. The fourth step of the application focusses on the identification and interpretation of these implications. This step considers the design challenges that occur because of the changes. The focus is on how the other layers of the framework are affected by the changes and hence what design challenges emerge.

Semi-structured interviews are conducted to collect the input about the needed changes and the potential design challenges due to the integration of hydrogen in the Dutch natural gas infrastructure. Seven Experts in the field of hydrogen and the natural gas infrastructure are interviewed.

4. Results and discussion

The results will be discussed along the four steps as described in the methodology. This section will end with a discussion about the results.

4.1 The natural gas infrastructure

The technical system of the gas infrastructure is mainly designed based on the liberalization of a vertically integrated monopoly that was built upon on the specific characteristics of the available volumes of natural gas, the present gas qualities, the public service characteristics of natural gas, and the possibility of natural gas buffer capacities. The latter determinants have resulted in a centralized natural gas infrastructure based on the top-down provision of gas in which the assets comply with specific gas quality standards. The network topology and buffer capacity are based on the centralized production and storage of large volumes of natural gas. The management of the gas transportation infrastructure is mainly conducted by the public system operators and the gas supply decisions are infringed by the government. The demand for natural gas and hence the network topology is basically stemming from the legal obligation to connect all the Dutch buildings to the public natural gas grids. The market design of the gas infrastructure is based on the functioning of the publicly owned and operated transmission and distribution grids. The wholesale market is basically facilitated by the transmission grid and the retail market by the distribution grids. The wholesale market is designed to allow every competent actor that is willing to trade gas to participate under the rules of the TSO and the regulator. The wholesale market is hence designed to allow for the competition in bulk gas, to enhance the security of supply, and to address the public service obligation connected to the natural gas provision. The retail market is designed to supply the smaller consumers that are not interested to be active in the natural gas trade. Basically, the retail market provides the consumers with a mean to buy gas competitively. The competitiveness in this sector is based on the ability of the retail suppliers to strategically buy gas in the wholesale market and resell it to the small-scale end-users. The retail market therewith enhances the market functioning of the wholesale market but only allows for the unilateral transactions of gas. The supply that is injected in the distribution grids is hence also unilaterally traded for regulated prices. The technical system and market designs can be argued to function complementary since they result in a reliable, acceptable, and affordable gas provision. Whether the latter performance criteria are satisfied and hence whether both designs function complementary is a matter of political stance and individual opinion.

4.2 Hydrogen infrastructure configurations

It is assumed that pure hydrogen gas will be transported through the existing pipeline networks of the gas infrastructure for the purpose of replacing natural gas in the heat provision to the Dutch residential and service sector. The hydrogen infrastructure configurations that are analyzed are therewith constrained by the exclusion of the alternatives to pipeline transport and the exclusion of alternative end-use sectors. The two hydrogen infrastructure configurations that are chosen hence only vary on the characteristics of the hydrogen production and storage since the transportation, and end-use applications are fixed. One hydrogen infrastructure configuration is mainly based on a centralized production of hydrogen and one is mainly based on a decentralized production of hydrogen. For both infrastructure options it is assumed that natural gas needs to be replaced by green or blue hydrogen. Figure 2**Error! Reference source not found.** schematically illustrates the hydrogen infrastructure options.

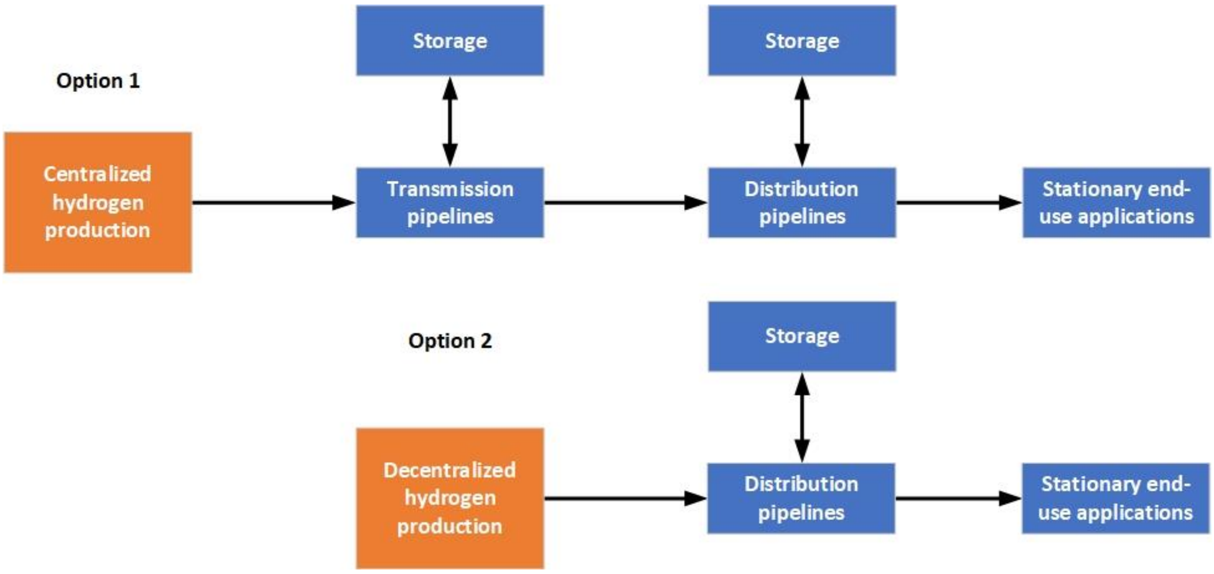

Figure 2: Schematic illustration of the chosen hydrogen infrastructure configuration

4.3 Replacements and adjustments in the natural gas infrastructure design because of the utilization of hydrogen

The changes that are identified are mainly caused by the characteristics of a starting gas infrastructure system with a new gas production segment that needs to transport, store, and use another quality of gas. The changes in the technical design are hence mainly caused by the new production segment and the new characteristics of the produced gas that introduces new requirements to the technical operation of the system. The changes in economic institutions are largely triggered by the characteristics of a starting infrastructure system with an immature market and high up-from investment costs. The changes in the roles and responsibilities of the actors are hence mainly triggered by the starting energy infrastructure, the new hydrogen production segment, and the new hydrogen gas qualities that need to be established.

The changes in the system design are needed regarding the instalment of enough hydrogen production capacity, storage capacity, and end-use equipment. The transportation infrastructure can be changed relatively easy in terms of the technology and costs. The interaction between the development of enough supply (i.e. production, storage, and transport capacity) and demand will be most challenging. The changes in the economic institutions require laws and regulations to change regarding various energy systems. The latter will be a complex and time-consuming activity including a variety of public and private actors on both the national as the supranational level. Since the utilization of hydrogen in the public gas grids is prohibited, changes in laws and regulations need to precede the changes in the technical system design. The latter implies that the development of a hydrogen gas infrastructure is strongly dependent on the development of the economic institutions applicable to the provision of hydrogen.

4.4 The design challenges of utilizing hydrogen

The design challenges follow from the elements that need to be added or replaced in the Dutch gas infrastructure when hydrogen is integrated. The technical system design challenges mainly exist since a new hydrogen gas production segment needs to be integrated and new gas qualities need to be produced, transported, stored, and consumed. The gas supply capacity and buffer capacity of a hydrogen gas infrastructure are significantly reduced because of the newly needed hydrogen production and storage capacities. The economic-institutional design challenges are mainly based on the notion that the emergence of enough hydrogen gas supply and demand will be impossible in a deregulated market on the short-term. The large-scale hydrogen investments that are needed in hydrogen production capacity, hydrogen buffer capacity, CCS infrastructure, hydrogen transport capacity, and hydrogen end-use equipment need long-term arrangements between the transacting parties. Adequate price-signals will not be present for hydrogen on the short-term and hence not incentivize parties to invest. The main design challenges that are the consequence of the new hydrogen production segment and the inexistence of a hydrogen market design will be elaborated on in this section.

4.4.1 Interaction with hydrogen energy input systems and markets

It is important to determine where in the gas infrastructure and on what scale specific hydrogen production activities are desired in terms of the availability and storability of the energy input needed to produce hydrogen. The latter challenge is important, since the energy input of the hydrogen productions segment will determine to a large extend what the security of supply of the new hydrogen system will be. Another challenge is to determine how the hydrogen tariff structure will be defined in the interaction with the other tariff structures of the needed energy inputs and substitutes. The tariff regulations regarding the taxation, CO_2 requirements, and large-scale investments in the various systems need to result in the fair competition between the various sectors in an international context.

4.4.2 Path-dependency in the transformation of the natural gas infrastructure

The design challenge is to safeguard the needed natural gas production, transport, and buffer capacity to produce adequate volumes of blue hydrogen and simultaneously address the need to transform the existing natural gas infrastructure to be compatible with the provision of hydrogen (i.e. to decline the natural gas production, transport, and buffer capacity). Since the production of hydrogen cannot be predominantly based on the production of green hydrogen on the short-term, the production of hydrogen from natural gas will be unavoidable. It is important to determine how the natural gas infrastructure will be transformed to ensure adequate amounts of gas production, transportation, and buffer capacities.

4.4.3 Integration of CCS infrastructure

The challenge is to determine for what time-span and what purposes CCS infrastructure will be integrated in the energy systems. CCS infrastructure is needed in the production of blue hydrogen and blue electricity. The carbon that is captured needs to be transported and stored and can potentially be used as feedstock in the industry. The transportation and storage can be conducted in the existing or in new pipelines and storage facilities.

4.4.4 Adequate hydrogen supply and demand and a hydrogen market

Adequate volumes of hydrogen supply and demand will be difficult to accomplish on the short-term in the absence of a well-functioning hydrogen market. The design challenge is to realize that enough supply and demand will be established for longer periods of time while simultaneously ensuring fair hydrogen prices and a competitive sector that is attractive to invest in. Direction from the government will be essential, since the current market design is not adequate to deal with the characteristics of a new hydrogen infrastructure.

4.4.5 The energy buffer capacity of the gas infrastructure

The buffer function of the natural gas infrastructure is important for the reliable functioning of various sectors such as the power sector, the district heating sector, the industry, and the built environment. The natural gas infrastructure is hence important for the security of the energy supply in the Netherlands. The challenge is to design a hydrogen gas infrastructure that addresses the buffer function of the gas infrastructure and its interaction with other systems. The production of green hydrogen will require the buffer capacity to be dependent on the storage of hydrogen gas. The production of blue hydrogen includes the possibility to use the buffer capacity of the existing supply chains that provide the energy input to produce hydrogen. The path dependency of transforming the natural gas infrastructure for the availability of natural gas is hence important.

4.4.6 Interaction with the electricity grid and district heating networks

The possibility to make hydrogen gas from electrolysis with heath as by-product changes the nature of the interaction between the gas infrastructure and the electricity infrastructure. The design challenges are to determine where in the electricity and gas infrastructure the possibility for conversion is viable, how these assets will be owned and operated, and how the conversion service will be transacted. The interactions between the district heating, electricity, and gas systems will change and it needs to be determined how they will interact in a future where environmental goals and renewable energy sources become more dominant. The total life cycle of an energy carrier, from primary energy source to end-use, needs to be included in the choice in which energy carrier is efficient to distribute, store, and consume for specific applications. The design challenge is hence to determine under what conditions the interactions between the various energy provision systems can be intensified from both an engineering and market design viewpoint.

4.4.7 The role of the transmission and distribution system operators

The public transmission and distribution system operators are not allowed, by the laws and decrees, to participate in any other activity that is not related to the provision of the energy carrier (i.e. electricity or gas) applicable to the specific energy infrastructure that they own and operate. It is hence prohibited to provide hydrogen gas. The design challenge is to determine what activities the transmission and distribution system operators can participate in under what conditions. The choice is relevant since the transformation of the gas infrastructure, to provide hydrogen, is dependent on the organization and the direction of the system operators in the emergence of enough hydrogen supply and demand. Moreover, the changing gas production, storage, and end-use possibilities and hence the changing possibilities to integrate various energy systems need to be organized and coordinated. The laws and regulations currently match the unilateral role of the system operators regarding the provision of individual energy carriers in individual systems.

4.4.8 Consumer sovereignty in the built environment and competition in between systems

The proposed regional energy strategies of the Dutch government shift the choice in energy carrier from the individual to the municipalities and the energy regions that they participate in. The design challenge is to determine if and to what degree the competition and consumers sovereignty in the distribution grids is hence desirable and possible. The perspective changes from a choice in a specific energy carrier for the provision of heat to a situation were a specific energy carrier is delegated and hence coupled to the choice to live somewhere. The current electricity and gas distribution systems are subject to a public service obligation to connect all buildings. The latter will not hold with the introduction of the regional energy strategies and the laws and regulations need to be adjusted.

4.4.9 Choice in ownership and decision right infringement regarding hydrogen production activities

There is no need to organize access to the hydrogen gas production segment and its operations as strict as with the natural gas production activities (i.e. mining activities). The design challenges in the infringement of ownership and decision rights are hence, how to design the laws and regulations in such a way that: enough hydrogen supply and demand will occur, the system will be efficient in terms of its economic and energetic performance, and that the system will be reliable in terms of the security of supply and the possibilities to interfere in the production activities. The ownership and decision rights need to be defined for the various hydrogen production activities that are possible on various scales. The entry conditions and infringement in ownership and decision rights determine largely which production facilities will emerge where and on what scale. The outcome of the ownership and decision rights regime hence determines to a large extend if and how the future hydrogen system will be designed and operated.

4.4.10 A shift from the centralized availability of gas to the local and regional supply of gas

When hydrogen gas is produced more decentral on the level of the distribution grids, by a larger number of production facilities, the gas supply volumes will shift from the current entry-points in the transmission grid to other entry-points in both the transmission and distribution grids. The interaction between the gas transmission grid and the distribution grids will fundamentally change due to the local gas supply. A design challenge is to determine to what extend and under what conditions the local hydrogen production facilities can emerge and inject into the distribution grids. When the local production facilities can emerge, it is important to determine how the local gas will be transacted. The technical system design challenge is hence to determine how the network topology and the operations of the gas transmission and distribution grids should change when the local hydrogen production facilities need to be connected. The economic-institutional design challenge focusses on modes of organization that structure how the local hydrogen producers can inject and transact their local available gas under what conditions.

5. Discussion and future research possibilities

This paper focusses on the techno-operational and economic-institutional implications that an integration of hydrogen can cause for the functioning of the Dutch gas infrastructure. The focus of the research is therewith mainly on the organizational challenges of an integration of hydrogen for the functioning of the gas provision. An assessment on the costs and environmental performance of the hydrogen infrastructure is excluded from the scope. Acceptability issues regarding the transformation of hydrogen are also excluded and the detailed hydrogen infrastructure design and performance are not addressed. The research does not include the interaction of a hydrogen system with possible acceptation issues regarding the hydrogen end-use technologies, the CCS infrastructure, the natural gas dependency, and the infringement of consumer sovereignty. The exact effect of a replacement of natural gas by hydrogen on the total system costs and the security of supply is also out of the scope. Uncertainty regarding the development of the prices of the hydrogen production technologies in the future introduces uncertainty regarding the specific possibilities of the adoption of the technologies. The following suggestions for future research question can potentially address the uncertainties around the results of the research conducted:

1. Under what conditions will hydrogen condensing boilers and hydrogen fuel cell technologies be adopted in the built environment?
2. Under what conditions and on what scale will the integration of CCS infrastructure be acceptable?
3. How are end-users in the built environment valuing consumer sovereignty?
4. Under what conditions and on what scale will the natural gas dependency be acceptable?
5. What will be the diffusion rate of sustainable gasses in the replacement of natural gas in the built environment?
6. What market designs enhance the emergence of hydrogen supply and demand on the short-term?
7. What is the effect of replacing natural gas by hydrogen on the affordability and availability of the gas provision?
8. What does a detailed design of a hydrogen production segment look like that addresses the environmental policy targets and the security of supply?
9. What does a detailed design of a gas storage segment look like when the public gas grids are strictly compatible with (near) 100% hydrogen gas?
10. What is the effect of the integration of the district heating, hydrogen gas, and electricity distribution grids on the total system costs and the total buffer capacity?
11. What are the needed regulatory alterations to allow for integrated energy systems in the Netherlands?

6. Conclusions and policy recommendations

The identified design challenges in the research illustrate the importance of the interrelatedness between institutions and technology and especially in their joint development for the way in which the gas infrastructure will be designed and operated in the future. The integration of hydrogen in the natural gas infrastructure is technically possible but requires clear political direction over time. The laws and regulations of the gas infrastructure basically determine how the infrastructure can develop. To develop a hydrogen infrastructure on the short-term, a more dominant role of state infringement in the Dutch energy systems seems necessary. The presence of the already proven hydrogen technologies includes the need to design the laws and regulations regarding the provision of hydrogen. The main design challenges of replacing natural gas by hydrogen gas in the Dutch gas infrastructure for the provision of gas to the residential and service sector are:

1. The need to develop a new gas production segment with new gas quality standards.
2. The need to define a market design regarding the inexistence of adequate hydrogen supply and demand.
3. The need to define the laws and regulations regarding the provision of hydrogen.
4. The need to define the interaction with other energy systems in terms of the technical systems and the market.
5. The need to define which hydrogen production technologies can emerge where under what conditions.
6. The need to determine how the buffer capacity in the gas system will be organized with respect to the total energy buffer capacity in the Netherlands.

To change a complex socio-technical system such as the natural gas infrastructure, policy targets need to be integrated in the total natural gas infrastructure design. The CO2 policy targets for example, need to be implemented in energy systems that are simply not designed to be carbon free. The technical design perspectives, design principles, and control mechanisms are based on the utilization of carbon containing gas. The Governance arrangements active in the gas market and the modes of organization subject to the gas transactions do not include the external costs of CO2 or the possibility to socialize the costs of improvements that serve the society in terms of total efficiency perspectives. The latter stresses the importance to consider a socio-technical approach in the design of energy infrastructures that includes the entire energy provision supply chain, from the primary energy source to the end-use. An integration of hydrogen will hence require important and fundamental choices in the design perspectives of our future energy systems. Critical issues regarding the formulation of adequate laws and regulations are:

1. The role of hydrogen in the current gas infrastructure and hence in the future energy systems.
2. The potential benefits of integrated energy systems in terms of their transmission and distribution activities and in terms of their markets.
3. The specific regulatory elaboration of the CO_2 goals regarding the Dutch energy systems and hence regarding the energy tariff structures.
4. The role of blue hydrogen and blue electricity production.
5. The role of the government and the public system operators in terms of the development of a hydrogen system and hence the development of hydrogen supply and demand.
6. The role of the buffer capacity of the current gas infrastructure in the reliable provision of energy to the built environment.
7. The adequateness of the current energy strategies and market design to replace natural gas in the built environment.
8. The degree of vertical and horizontal integration of the system operators.
9. The taxation of the production of hydrogen and moreover, the taxation of grey hydrogen in combination with grey electricity and heat.
10. The degree of consumer sovereignty in the built environment.

Policy targets alone will not be enough to address the design choices that need to be made. The actual natural gas infrastructure design should address the design choices in its social and technical elements, and in the interaction between them. A hydrogen gas infrastructure is dependent on the change over the entire natural gas infrastructure. When the policies regarding the development of the gas infrastructure remain in the scope of the current natural gas system and hence in the scope of the current provision of energy based on the combustion of fossil fuels, the important characteristics of a hydrogen infrastructure will be neglected. Hydrogen will be integrated in a system that is designed for the combustion of fossil fuels. The system will be unavoidably inefficient for the provision of hydrogen and the way in which the future energy systems need to be designed.

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