Applied Energy 88 (2011) 3821–3831

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The cost of pipelining climate change mitigation: An overview of the economics of CH_4, CO_2 and H_2 transportation

B.C.C. van der Zwaan [a,b,c], K. Schoots [a,*], R. Rivera-Tinoco [a], G.P.J. Verbong [d]

[a] Energy Research Center of the Netherlands (ECN), Policy Studies Department, Amsterdam, The Netherlands
[b] Columbia University, Lenfest Center for Sustainable Energy, The Earth Institute, New York City, NY, USA
[c] School of Advanced International Studies, Johns Hopkins University, Bologna, Italy
[d] Eindhoven University of Technology, Department of Industrial Engineering & Innovation Sciences, Eindhoven, The Netherlands

ARTICLE INFO

Article history:
Received 24 January 2011
Received in revised form 29 April 2011
Accepted 2 May 2011
Available online 8 June 2011

Keywords:
Natural gas
Carbon dioxide
Hydrogen
Climate control
Pipeline costs
Learning curves

ABSTRACT

Gases like CH_4, CO_2 and H_2 may play a key role in establishing a sustainable energy system: CH_4 is the least carbon-intensive fossil energy resource; CO_2 capture and storage can significantly reduce the climate footprint of especially fossil-based electricity generation; and the use of H_2 as energy carrier could enable carbon-free automotive transportation. Yet the construction of large pipeline infrastructures usually constitutes a major and time-consuming undertaking, because of safety and environmental issues, legal and (geo)political siting arguments, technically un-trivial installation processes, and/or high investment cost requirements. In this article we focus on the latter and present an overview of both the total costs and cost components of the distribution of these three gases via pipelines. Possible intricacies and external factors that strongly influence these costs, like the choice of location and terrain, are also included in our analysis. Our distribution cost breakdown estimates are based on transportation data for CH_4, which we adjust for CO_2 and H_2 in order to account for the specific additional characteristics of these two gases. The overall trend is that pipeline construction is no longer subject to significant cost reductions. For the purpose of designing energy and climate policy we therefore know in principle with reasonable certainty what the minimum distribution cost components of future energy systems are that rely on pipelining these gases. We describe the reasons why we observe limited learning-by-doing and explain why negligible construction cost reductions for future CH_4, CO_2 and H_2 pipeline projects can be expected. Cost data of individual pipeline projects may strongly deviate from the global average because of national or regional effects related to the type of terrain, but also to varying costs of labor and fluctuating market prices of components like steel.

1. Introduction

The investment costs associated with the distribution of (combinations of) gases like CH_4, CO_2 and H_2 may become an important factor for the success or failure of transforming present energy production and consumption into a sustainable energy system based on clean (fossil fuel) technologies. Several different gas delivery modes exist. In gaseous form transportation takes normally place via pipelines or in gas cylinders.[1] In liquid form gases are usually transported via pipelines or in tanks.[2] No large-scale CH_4, CO_2 or H_2 transportation exists in solid form.[3] In contrast to retaining CH_4, CO_2 and H_2 in gaseous phase, transforming them in liquid form and keeping them at the right temperature and pressure adds to the total transportation costs. The energy-equivalent capacity of transportation, however, can be extended considerably when transporting in liquid rather than gaseous phase. Moving large quantities of liquefied gas may thus result in lower costs per unit of delivery.

The choice of transportation ultimately depends on the expected total demand for the gas, the transportation distance, and the number of delivery points and their capacity. This has been investigated for H_2 distribution by Yang and Ogden [1]. They show that for a city with a low number of H_2 fuelling stations with each a capacity in the range of 500 kg/day, transportation in gaseous form via trailer tubes is the lowest-cost delivery mode. For replenishing 1000 kg/day fuelling stations, delivery in liquid phase via trucks becomes more cost-effective when the number of fuelling stations in the city is small. As the demand for H_2 increases, however, whether by an increase in the density of fuelling stations or an increase of the capacity of individual fuelling stations, the preference gradually

* Corresponding author. Tel.: +31 224 564143; fax: +31 224 568339.
E-mail address: schoots@ecn.nl (K. Schoots).

[1] A wide variety of gas cylinders exists, ranging from small 0.4 l cylinders to large trailer tubes with an outer diameter of 56 cm and a length of 12 m.

[2] Liquid gas tank transportation takes place in widely variable size, from small tanks of 0.1 m^3 to ships holding over 100,000 m^3 of liquid gas.

[3] For some applications CO_2 ice is used as coolant, in which case evaporated CO_2 is released into the atmosphere.

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.05.019

shifts to gaseous delivery via pipelines, as they become the option with the lowest levelized costs.

Pipelines are the transportation mode of choice for gases in general when demand is high and supply has a base-load character. For CH_4 this transportation method is today already most common. Once the transportation of CO_2 and/or the distribution of H_2 successfully enter the energy system as greenhouse gas control options on a large scale, we expect that this delivery mode will also apply to these two gases. We therefore investigate the transportation of CH_4, CO_2 and H_2 through pipelines. The correctness of our assumption of successful large-scale market penetration of the transportation of CO_2 and H_2 critically depends on whether significant CO_2 reductions are achieved through CCS and whether the establishment of a hydrogen economy materializes. In this paper we inspect the current total and detailed breakdown of pipeline construction costs. We next analyze the sensitivity of overall pipeline construction costs to fluctuations in cost components such as materials, labor and right-of-way. As a corollary to our analysis we gather data on cumulative installed pipeline length to date, as well as on (total and component) cost developments in the past, to inform public policy and strategic planning, and in an attempt to develop and evaluate learning curves for pipeline construction costs.

Material costs of pipelines are determined by their dimensions (length and diameter) and the choice of construction material. The design of the pipeline system, which also includes initial compressors and booster stations, is determined by the flow conditions of the gas (which may locally differ over the length of the pipeline). Flow conditions inside a pipeline are determined by pressure, temperature and gas composition and are neither steady nor isothermal. Steady-state isothermal models are thus not suitable for optimizing the design of pipelines. In practice intricate computer simulations are used instead, that determine the optimal pipeline size, the necessary operating pressure and the required power for initial compressors and intermediate booster stations. To some degree the number of booster stations can be chosen at will. Installing fewer booster stations involves higher total investment costs, as it requires a more powerful initial compressor station to compensate for the lower intermediate booster capacity. The pipeline then also needs to be constructed with a larger wall thickness in order to deal with the higher operating pressures. On the other hand, whereas a larger number of booster stations would decrease the overall investment costs, it leads to higher operating costs as a result of the more complex operation procedures associated with their usage.

Authorities may enforce legislation on pipeline safety by setting a maximum operating pressure (MOP). The allowable MOP is determined by the diameter of the pipeline, its wall thickness, its construction material, and the strength of its longitudinal welds, as well as the pipeline location. The higher the population density in a particular area, the lower the MOP. The material choice is determined by minimum yield strength, fracture toughness, ductility and weldability requirements, as well as the chemical properties of the gas transported. Pipelines can be constructed from both (longitudinal) welded pipes and drawn (seamless) pipes. Usually pipelines are designed oversized with respect to the expected initial demand, in order to absorb possible market growth or demand differences between peak and off-peak periods. Instead of constructing a pipeline with a larger diameter, one may employ peak-shaving or storage facilities, depending on what solution is most cost-effective.

Apart from the design process, the construction of a pipeline involves obtaining permits and clearances, making the approved work area ready for construction, constructing the pipeline and making the pipeline ready for use. The construction process also includes applying corrosion protection and water pressure testing. Trenching should be added to these activities for subterranean pipelines. For each pipeline construction project the terrain may be different. Even along the route of a single pipeline, conditions may alter and include a mix of cultivated land, grassland, forests and cities. On a pipeline trajectory constructors may have to confront height differences and river crossings, which affect overall costs. Each pipeline construction process is influenced by local, national or regional legislation. These factors affect the corresponding labor costs, as well as cost components related to surveying, engineering, supervision, allowances, contingencies, overhead and filing fees. Right-of-way expenses often add to total pipeline costs, including e.g. ownership matters. Indeed, the design and construction of pipelines are lengthy and complex processes, in which many factors influence overall costs. We here analyze a simplified case of gas transmission to provide a basic understanding of the main cost dynamics.

Data consistency is key to investigate the evolution of pipeline construction costs: it has been one of our selection criteria. To make available data mutually comparable, we express costs in US$ in the reference year 2000. For ease of exposition we quote construction costs per kilometer of pipeline. Pipeline design characteristics, like aboveground or subterranean, covered or uncovered, trenched or trench-less, as well as charges due to differences in terrain, are averaged out in our study by including a large set of different projects. We circumvent the country-dependency of pipeline costs by only assessing construction costs in the US. Initial compressors and booster stations are excluded from our cost analysis. In Sections 2, 3 and 4 we give for respectively CH_4, CO_2 and H_2 pipelines an overview of their total construction costs and breakdown in main cost components, and extensively describe the historic developments of these costs. In Section 5 we assess whether we can distinguish cost reductions and learning behavior for total pipeline construction costs. Section 6 summarizes and discusses our major findings and provides a couple of conclusions for public policy and strategic planning purposes. The learning curve methodology used for Section 5 is briefly recapitulated in Appendix A.

2. Transportation of CH_4

The costs of completed CH_4 pipeline construction projects have been thoroughly reported in the Oil and Gas Journal (OGJ: [2–25,64]. Based on these sources, as well as publications by Castello et al. [26], Gasunie [27–29] and Parker [30], we analyze the evolution of CH_4 pipeline construction costs in recent decades.

2.1. Construction costs

Fig. 1a–g shows the development of construction costs in the US for onshore CH_4 pipelines as function of time for a range of different pipeline diameters. For 61 and 91 cm diameter pipelines we retrieved data on total costs covering a time frame from 1964 to 2008, for 76 cm diameter pipelines from 1967 to 2008, and for 20, 30, 41 and 51 cm diameter pipelines from 1976 to 2008 [2–5,27–29]. The construction costs reported in OGJ distinguish between costs for materials, labor, right-of-way and miscellaneous contributions. Miscellaneous costs are those associated with surveying, engineering, supervision, interest, administration, overhead, contingencies, regulatory fees and allowances for funds used during construction. In total we assessed 1577 projects during which a total pipeline length of 80141 km was constructed. The detail of data reported in OGJ allows investigating the development of cost components separately between 1976 and 2008.

Comparing pipeline construction costs between different projects is often difficult as a result of the influence terrain may have on these costs. The location, i.e. country or region in which a pipeline is placed, may also affect construction costs considerably.