International Journal of Greenhouse Gas Control 5 (2011) 1614–1623

Contents lists available at SciVerse ScienceDirect

International Journal of Greenhouse Gas Control

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

Historical variation in the capital costs of natural gas, carbon dioxide and hydrogen pipelines and implications for future infrastructure

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ARTICLE INFO

Article history:
Received 23 January 2011
Received in revised form
21 September 2011
Accepted 29 September 2011
Available online 24 October 2011

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

ABSTRACT

The construction of large pipeline infrastructures for CH_4, CO_2 and H_2 transportation 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 paper we focus on the latter and present an overview of both the total costs and cost components of the transmission 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 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. Our main finding is that the economics of CH_4, CO_2 and H_2 transportation through pipelines are volatile. In particular for CH_4 and CO_2 the overall trend seems that pipeline construction costs have not decreased over recent decades or, at least, that possible reductions in overall costs have been outshadowed by the variability in the costs of key inputs. We speculate on the reasons why we observe limited learning-by-doing effects and expect that negligible construction cost reductions for future CH_4 and CO_2 pipeline projects will materialize. Cost data of individual pipeline projects may strongly deviate from the global average because of national or regional effects, such as related to varying costs of labor and fluctuating market prices of components like steel. We conclude that only in an optimistic scenario we may observe learning effects for H_2 pipeline construction activity in the future, but there are currently insufficient data to fully support the limited evidence for this claim, so that the uncertainty of this prediction for now remains large.

1. Introduction

Natural gas, carbon dioxide and hydrogen may play a key role in establishing a sustainable energy system: natural gas is the cleanest and least carbon-intensive fossil fuel; carbon dioxide capture and storage (CCS) can significantly reduce the climate footprint of particularly electricity production with coal, natural gas and oil fuelled power plants; hydrogen can be used for fuelling zero-emission vehicles. While the latter two are usually transported in close to pure streams of CO_2 and H_2, respectively, the former may often consist, when transmitted, mostly but not exclusively of CH_4. The composition of natural gas at the well-head can vary significantly between different production fields. Usually it consists of a mixture of hydrocarbon gases, carbon dioxide, nitrogen, hydrogen sulphide, oxygen, water vapour and traces of other (rare) gases. It typically contains 70–90% methane and 0–20% other hydrocarbons like ethane, propane, butane and pentane (NaturalGas, 2009). The definition we use is that of refined 'dry' natural gas, which mostly consists of methane. In the remainder of this paper we use the terms 'methane', 'natural gas' and 'CH_4' interchangeably.

The design and construction of pipelines for the transportation of these three gases is a lengthy and sometimes complex process, in which many factors may influence the overall costs (CO_2 Europipe, 2011; NaturalHy, 2011). The investment costs associated with the transmission of CH_4, CO_2 and H_2, in particular by pipeline, 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. In this paper we therefore investigate for these gases the current total and detailed breakdown of pipeline construction costs. We next inspect 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

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doi:10.1016/j.ijggc.2011.09.008

component) cost developments in the past, to inform both public policy and strategic planning, and in an attempt to develop and evaluate learning curves for pipeline construction costs.

Several publications have asserted that there is significant cost reduction potential for pipeline construction activities. For example, Zhao and Schrattenholzer (2000) advocated that learning can be discerned for the development of international transmission lines of natural gas. Yang and Ogden (2007) have extensively described the conditions under which the costs of H_2 distribution, including via pipelines, can be minimized. On the contrary, in the present paper we argue that the economics of CH_4, CO_2 and H_2 transportation through pipelines are volatile and that pipeline construction costs have not decreased over recent decades or, at least, that possible reductions in overall costs have been dwarfed by the variability in the costs of key inputs. This assertion affects the claim that CCS systems may be subject to significant cost reductions (IPCC, 2005).

Pipelines can be subdivided in two main categories according to the area over which they operate: distribution pipelines (for short lengths) and transmission pipelines (for long distances). As most information is available on the latter category we focus in our analysis on transmission pipelines, while in the remainder of this article sometimes referring to them as simply pipelines or lines. Wherever in the following we use the notion ‘distribution’ it is only done so as a synonym of ‘transportation’, not in association with the words ‘pipelines’ or ‘networks’. Hence we do not further inspect the other important pipelining subject, of more local networks and relatively short-distance distribution, as they have been extensively studied already (see, notably, Dooley et al., 2009; Johnson and Ogden, 2010). In Sections 2–4 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 potential cost reductions and meaningful 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.

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: True, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003; True and Stell, 2004; Smith et al., 2005; Smith, 2006, 2007, 2008, 2009). Based on these sources, as well as publications by Castello et al. (2005), Gasunie (1963, 1967, 1968) and Parker (2004), we analyze the evolution of CH_4 pipeline construction costs in recent decades. To make all data throughout this paper mutually comparable, we express costs in US$ in our year of reference 2000, for all three gases. For ease of exposition we quote construction costs per kilometer of pipeline. Specific pipeline design characteristics, like aboveground or subterranean, covered or uncovered, trenched or trench-less, as well as charges due to differences in terrain, are eliminated in our study through an averaging out over many pipeline projects. We circumvent the country-dependency of pipeline costs by only assessing construction costs in the US.

The full costs of gas transportation include the compression system. Although calculations of the optimum cost level usually prescribe the use of a smaller pipeline diameter and more frequent installation of booster stations, in practice, construction of trunk pipeline systems usually err on the side of installing fewer boosters and using larger diameter lines than the minimum cost option would suggest. The reason for this probably lies in operational issues including logistics of getting power and maintenance

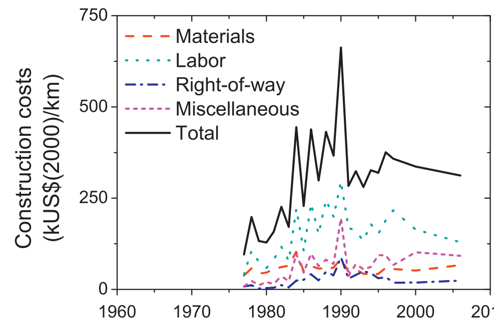

Fig. 1. Construction costs of 30 cm diameter, onshore CH_4 pipelines between 1977 and 2006.
Data from Gasunie and OGJ.

crews to booster stations in remote locations. As we are mostly interested in the construction costs of pipelines themselves, initial compressors and booster stations are excluded from our cost analysis.

2.1. Construction costs

Fig. 1 shows the development of construction costs in the US for onshore CH_4 pipelines as function of time for a pipeline diameter of 30 cm. We retrieved cost data on several different pipeline diameters showing similar trends (van der Zwaan et al., 2011). 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 (Gasunie, 1963, 1967, 1968; True, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003; True and Stell, 2004; Smith et al., 2005; Smith, 2006, 2007, 2008, 2009). 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 80,141 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. Technical difficulties associated with the placement of pipelines in lesser accessible terrain typically cause costs to rise. Table 1 shows the extra charges, as quantified by the IEA (2002), that pipeline building may encounter. These charges apply in principle to any pipeline, regardless of its size or the type of gas that is transported. In highly urbanized localities like cities, pipeline

Table 1
Terrain charges for CH_4 pipeline construction.

Terrain	Terrain factor
High urbanization	+700 kUS$(2000)
Low urbanization	
>50% mountainous land	×1.5
<20% mountainous land	×1.3
Cultivated land	×1.1
Jungle	×1.1
Stony desert	×1.1
Wooded land	×1.1
Grassland	×1.0

Data from IEA (2002).

Table 2
Country and region charges for CH_4 pipeline construction costs.

Country/region	Location factor
UK	×1.2
Australia/New Zealand	×1.0
Europe	×1.0
Japan	×1.0
US/Canada	×1.0
Equatorial Africa	×0.9
Middle East	×0.9
North Africa	×0.8
South America	×0.8
South-East Asia (excl. Japan)	×0.8
China/Central Asia	×0.7
Indian subcontinent	×0.7
Russia	×0.7
South Africa	×0.7

Data from IEA (2002).

construction costs can be raised by as much as 700 kUS$(2000)/km – but such a value may strongly differ from one urban construction project to another. From the OGJ data depicted in Fig. 1 we observe that construction costs may in exceptional cases rise to some 1.5 million US$(2000)/km (typically in cities). In low urbanized areas like arable land and forests, pipeline construction costs should be increased by 10–50% with respect to the corresponding costs on grassland (see Table 1).

The country or region in which a pipeline is located may also influence its construction costs significantly. Building a pipeline in developing countries is usually less expensive than in developed countries, mostly as a result of wage differences. Right-of-way costs can also differ between states: since these are primarily related to legal and permitting issues, they are not necessarily connected to a nation's level of development. The IEA (2002) presents overall correction factors for many countries and regions to account for these variabilities. These numbers, summarized in Table 2, express the impact of location on pipeline construction costs with respect to reference costs prevailing in the US. For the purpose of this paper we avoided construction cost variations between countries as a result of currency exchange fluctuations and interpretations by only using data expressed in US$. The data we retrieved primarily relate to projects realized in the US, and some in Europe, but all are expressed in US$. Currency corrections, through Purchasing Power Parities (PPPs) or Market Exchange Rates (MERs), are thus not required.

For the purposes of this paper, in order to reduce the effect of terrain charges, we use for each pipeline diameter cost data in which this factor is averaged out over all projects in a given year. In some years, the number of pipeline projects reported for a particular diameter is only one or two. We consider these cases insufficient, as the terrain charge cannot be averaged out effectively. We have therefore excluded these data points from most of our analysis, as we did for Fig. 1. As this figure demonstrates, over the past 30–40 years the costs of pipeline construction have not come down. Rather, several cost components are volatile and total construction costs even show a slightly upward trend (or at best fluctuate around a more or less stable mean). We determine the composition of construction costs for each pipeline diameter by averaging both the annually reported total costs and the cost contributions from each of the components between 1998 and 2008. In this case we do not exclude years with only one or two pipeline construction projects. Fig. 2 depicts the result for 30 cm diameter pipelines, which demonstrate the relative size of each of the four main cost shares. When applied to other pipeline diameters as well, this construction costs analysis shows that the total costs for pipeline construction (indicated below the pie diagram) increase with pipeline diameter. It turns out that the relation between pipeline diameter and total costs is close to linear. Our total cost data compare well with the pipeline construction costs of 713 kUS$/km reported by Parker (2004), and deviate by about 10% from the 786 kUS$/km level reported by Castello et al. (2005), both for 30 cm diameter pipelines. When comparing Fig. 2 to pie diagrams from other pipeline diameters, the contribution of material costs increases with pipeline diameter, while labor costs tend to decrease. This effect, however, is partially shielded by scattering in right-of-way and miscellaneous costs.

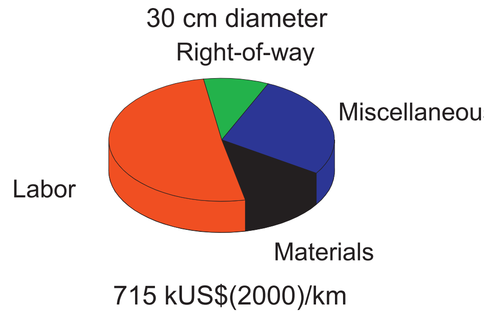

Fig. 2. Average cost breakdown for 30 cm diameter, onshore CH_4 pipeline construction between 1998 and 2008.
Data from Gasunie and OGJ.

In order to better explain the development of total pipeline construction costs, we further investigate the evolution of the four main cost categories. For each cost component, of all pipeline diameters, we determine an annual cost index relative to the component's costs in 2000 (which we set at level 100, in arbitrary units). These four indices are based on costs to which the inflation correction was applied. The four indices as function of time reflect the development of costs for each of the four components. Since we removed the information on the absolute value of the cost components, we can average the evolution of individual cost shares over different pipeline diameters. The resulting cost indices for materials, labor, right-of-way and miscellaneous costs are shown in Fig. 3a–d.

The material cost index is compared with the Producer Price Index (PPI) for iron and steel (US DOL, 2009). Especially from 1990 onwards, these two independently determined indices show overall a good match. Deviations between them may originate from the duration and timing of contracts between steel producers, pipeline manufacturers and construction companies, as well as hedging strategies by each of these parties. As one can conclude from Fig. 3a, the evolution of material costs over the last 20 years can mainly be attributed to market developments for the price of steel. The cost indices for labor and miscellaneous contributions are compared to the US consumer price (i.e. US$ inflation) index (US DOL, 2009). As can be seen from Fig. 3b, the mean labor cost index almost perfectly fits the evolution of this price index, which shows that US pipeline sector wages on average closely follow US$ inflation. Many of the components that together form the class of miscellaneous costs strongly depend on labor costs. It is therefore not surprising that this category also neatly follows the development of the US$ inflation index (which we just demonstrated to be a good indicator for the level of wages). Right-of-way costs strongly depend on land prices, which include fees set by local governments, legal costs and permit prices. We therefore compare right-of-way costs to the aggregated US land price index (Lincoln Institute, 2010). The right-of-way cost index is an indicator reflecting local conditions, which may play a role in de development of specific pipeline projects such as possible public resistance. Local conditions may of course differ from overall national conditions reflected in the aggregate index. This may explain the apparent deviations of the right-of-way cost index from the aggregate US land price index depicted in Fig. 3c, particularly during the last decade. Overall, however, we

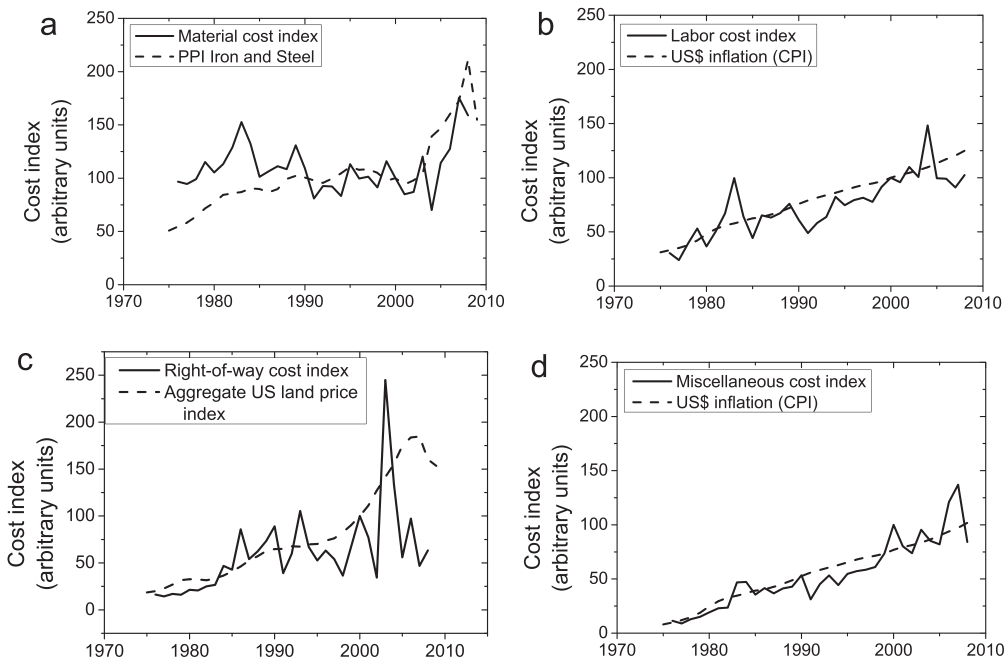

Fig. 3. CH_4 pipeline construction cost component indices (solid lines) matched with price indices (dashed lines): US producer price index for iron and steel for (a), US consumer price index for (b) and (d) and aggregate US land price index for (c).

think there exists fair correlation between the two indices. We thus argue that, like for the last two decades, total pipeline construction costs are likely to continue following the sum of volatile market prices for each of its cost components – cost reductions attributable to learning are unlikely, as so far no such effects have been observed.

In stead, because we included the same inflation correction to all cost data, we observe an equal structural rise in costs for all cost components. This effect may have three reasons (Kramer, 2009). First, it may be attributed to gradually tightening environmental and safety requirements for pipelines. A second possible cause for structural price increases may be that the tendering of pipeline construction projects is not entirely price driven, but also influenced by the trust investors have in particular contractors for being capable of successfully finishing projects. A third reason might be that the limited number of contractors in the field of pipeline construction is capable of exercising market power, as long as they stay within reasonable limits of price increases.

2.2. Cumulative pipeline construction

Pipeline construction began in the US with the first oil finds in the mid 19th century. Since we have not been able to find annually constructed pipeline mileage data before the 1980s (or total operational pipeline mileage data before the 1970s), we cannot reconstruct a reliable value for the cumulative length of deployed CH_4 pipelines in the US (van der Zwaan et al., 2011). For example, Castello et al. (2005) claim that by the end of 2003 1,750,000 km of pipeline existed in the US, of which 525,000 km were transmission pipelines; OGJ reports only 303,000 km. We expect that for pipelines constructed elsewhere in the world (like in Africa, Asia, Europe and countries of the former USSR) it would be similarly difficult to calculate figures for cumulative installed capacity. For some of these regions, a lack of available documentation means that it may be more intricate to derive such numbers.

3. Transportation of CO_2

The transportation of CO_2 distinctively differs from that of CH_4. The phase diagram of CO_2 shows that beyond a pressure of 74 bar and a temperature of 31 °C, i.e. the critical point, CO_2 becomes a supercritical fluid. As pipelines are usually operated at pressures between 100 and 150 bar, the transportation of CO_2 more resembles that of a liquid than a gas. One of the consequences for CO_2 pipeline design is that, after the initial compression, booster stations along the pipeline are not equipped with gas compressors but fluid pumps.

Still, like for CH_4, CO_2 pipelines can be constructed from low alloys and carbon steel, provided that the transported gas is dry. When the humidity becomes high, CO_2 may dissolve in condensed water and can react, as carbonic acid, with its environment and thus corrode the pipeline wall. Pipeline corrosion can be prevented by keeping the relative humidity of the gas below 60% and thus avoiding condensation of moisture (see e.g. IPCC, 2005). In practice, extra measures like the application of protective layers like polymer or corrosion-resistant alloy coatings are required (accompanied with an additional price tag) to prevent the quality of the pipeline metals from deteriorating too quickly (IPCC, 2005).

Gaseous CO_2 is denser than air. In case of a pipeline seepage it therefore accumulates on the ground, before it slowly diffuses into the ambient atmosphere. The fact that CO_2 resulting from pipeline leakage locally replaces oxygen, or reduces the oxygen concentration, poses serious safety concerns, especially when leakage occurs

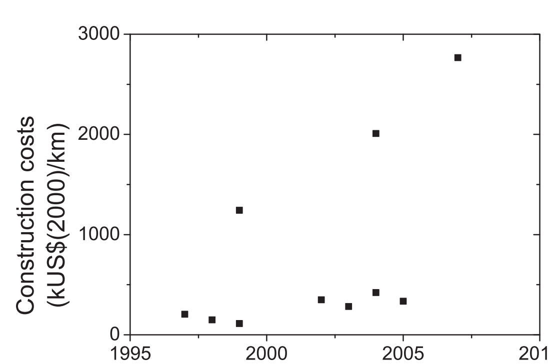

Fig. 4. Construction costs for 30 cm diameter CO_2 pipelines.

Table 3
Construction cost breakdown for a 30 cm diameter CO_2 pipeline.

Component	Costs (kUS$(2000)/km)
Materials	187
Labor	358
Right-of-way	44
Miscellaneous	199
Total mean (without terrain)	788

in protected or closed spaces with limited air circulation. Seepage of CO_2 involves risks of suffocation for animals and humans. By installing sensors along CO_2 pipelines, possible leakage can be detected in view of avoiding casualties. However, unless a continuous linear system could be developed, point detectors are unlikely to provide full coverage. Lines could be fitted with strategically placed detectors between the line and nearby housing as is current practice with H_2S pipelines.

The behavior of CO_2 in open air is different from that of CH_4: the latter is more volatile and has a lower density than air thus rises when it leaks. On the other hand, the fact that CO_2 is not combustible yields a certain advantage in comparison to CH_4 and H_2.

3.1. Construction costs

We obtained cost data for CO_2 pipelines constructed between 1997 and 2008 from a series of public sources (in particular Denbury, 2008; Groenenberg et al., 2009; Hamelinck et al., 2001; Hendriks et al., 2004; IEA, 2009; IPCC, 2005; NEBC, 1998; Northway, 2006; Torp and Brown, 2004; UK DTI, 2002; Vandeginste and Piessens, 2006). Many of these publications also contain information on pipeline length and diameter, which enables us to express costs per km and to convert cost data to our reference of choice, i.e. a diameter of 30 cm. For the latter we use our estimated linear diameter dependency of CH_4 pipeline costs discussed in Section 2.1. We correct data for currency and inflation effects so as to obtain costs expressed in US$(2000)/km. The result is shown in Fig. 4. The number of CO_2 pipeline examples with known costs is unfortunately too small to allow averaging out costs over multiple construction projects. The large scattering observable in Fig. 4 can thus be attributed to widely diverging characteristics of individual pipeline projects, such as related to terrain, country, right-of-way, permitting and regulation.

The average construction cost for a 30 cm CO_2 pipeline without exceptional additional terrain charges was, between 1997 and 2008, approximately 788 kUS$(2000)/km. Due to the large spread in available data – by as much as an order of magnitude, as illustrated in Fig. 4 – this average possesses limited value for estimating actual CO_2 pipeline costs. This overall figure includes costs associated with materials, labor, right-of-way fees and miscellaneous contributions. A breakdown of total CO_2 pipeline construction costs into individual cost contributions has been investigated by Vandeginste and Piessens (2006). We here apply their cost calculation methodology (essentially the same as the one used by Parker (2004) but applied to CO_2 pipelines) to our central mean, the result of which is shown in Table 3.

3.2. Cumulative pipeline construction

When searching for potential new natural gas fields, explorers in the US discovered sites that contained gases with high concentrations of CO_2. Such fields were found especially in the upper and lower Colorado region, as well as in Wyoming, North Dakota and Mississippi. In order to increase fossil fuel supply and thereby improve energy security the US government stimulated enhanced oil recovery in the 1970s and 1980s. The discovered CO_2 fields could ideally be used for this purpose, but necessitated the construction of transmission pipelines from these fields to the Mexican Gulf Coast region where most of the US oil production takes place (Kinder Morgan, 2009; UK DTI, 2002). The first CO_2 pipeline was built in 1972 in West Texas between McCamey and Kinder Morgan's SACROC oil field.

To date some 4580 km of pipeline has been built with as main purpose the transportation of CO_2 (Duncan et al., 2009; Kinder Morgan, 2006; IPCC, 2005; PGJ, 2003; Reuters, 2009; UK DTI, 2002). Pipelines that were initially constructed to transport other substances, such as oil or natural gas, but were later converted to carry CO_2, are not included in this figure. This cumulative pipeline length agrees well with the estimate of 4200 km quoted by the IPCC (2005). Apart from the pipeline of the Dakota Gasification Company to Weyburn in Canada and the Bati Raman pipeline in Turkey, essentially all CO_2 pipelines are located in the US: there is so far no significant deployment of CO_2 pipelines in the rest of the world. Short (distribution) pipelines exist at many locations in and around chemical plants, but we do not take these into account since we are mostly interested in long-distance transmission pipelines. We know of at least two major pipelines that were initially designed for oil or gas transportation but were later converted to transmit CO_2. The Cranfield pipeline in the US, running from near the Mississippi–Louisiana border to Jackson Dome in Central Mississippi, was initially constructed in 1963 as a CH_4 pipeline and was later used for CO_2 transportation (Denbury, 2006; Duncan et al., 2009). The Dutch NPM oil pipeline built in 1969 between Rotterdam Botlek and Amsterdam West is now used to transport CO_2 to greenhouses (OCAP, 2009; PRDF, 2005).

4. Transportation of H_2

The transportation of H_2 through pipelines demands special precautions with respect to both pipeline material and operating conditions. A major challenge derives from the fact that H_2 is able to diffuse into steel. Molecules of H_2 may dissociate at the surface of alloys into two H atoms, which can then migrate deep into the material. Subsequent to diffusion, H atoms can recombine in microvoids inside steel to form again molecular H_2 gas. Consequently pressure builds up in these voids, which decreases the ductility and tensile strength of the steel up to a point where it may rupture. This process, called H_2 embrittlement, makes especially strong steel types with high manganese and carbon content vulnerable for cracking. A possible solution to avoid fracturing is the use of thick low strength steel, and a gas humidity at values below 60% (IEA, 2002).

Another cause of steel erosion is H_2 attack. This process takes place when the partial pressure of H_2 exceeds 100 bar and the gas temperature rises above 200 °C (Castello et al., 2005; IEA, 2002). These conditions do not only allow H_2 to diffuse in pipeline alloys at a higher rate, but also enables H atoms to react with carbon, one of the steel's components. The product of this reaction is gaseous methane that accumulates in pockets at grain boundaries and microvoids in the material structure. The increasing pressure inside these voids leads to a decrease in ductility and tensile strength. Moreover, methane pockets may eventually coalesce and thereby gradually form large cracks in steel.

Compressing and pumping H_2 requires a different approach from that of heavier gases. The small molecular size of H_2 makes centrifugal compression, applied when handling large volumes of CH_4, impractical for H_2. For the currently prevailing low flow rates, reciprocating compressors suffice to compress H_2. These compressors possess a higher number of moving parts than centrifugal compressors, produce more vibrations and require more maintenance, but can achieve higher pressures. The latter reduces

Table 4
Construction cost breakdown for a 30 cm diameter H_2 pipeline.

Component	Costs (kUS$(2000)/km)
Materials	143
Labor	463
Right-of-way	69
Miscellaneous	179
Total mean (without terrain)	854

the need for booster stations along the pipeline (Castello et al., 2005).

The amount of energy stored in a unit volume of gas is approximately three times lower for H_2 than for CH_4 under the same pressure and temperature conditions. However, because of the lower density of H_2, lines of equal diameter and pressure drop still have 80–98% of the energy capacity to transport H_2 as compared to natural gas (Haeseldonckx and D'haeseleer, 2007). The current compression technology is not really capable of reaching high flow rates, so that H_2 is normally transported at a relatively low pressure and temperature. This avoids material erosion. If one were to aim for achieving higher energy flows, a H_2 pipeline would need to be constructed significantly more robust than a CH_4 pipeline, so as to better resist material degradation and thus prevent pipeline rupture and gas leakage. This would increase the construction, operation and maintenance costs of H_2 pipelines which may cancel overall cost reductions from increasing the energy flow.

Transport of H_2 via pipelines also differs from that of other substances in that other sensor types are needed to detect possible seepage. Leaky H_2 pipelines pose less of a problem than when CO_2 is transported, since H_2 is (like CH_4) lighter than air and is particularly volatile. No particular health risks are involved in potential H_2 leakage. Present right-of-way regulations should probably be adapted and updated, since the ones now in place for oil and gas pipelines probably do not include all specificities of H_2 transportation.

4.1. Construction costs

Similar to the transportation of other gases, the investment costs required for the construction of H_2 pipelines depend on four main categories of components: the materials used, the labor for construction, right-of-way fees and miscellaneous contributions. The relationship between the construction costs of H_2 and CH_4 transmission pipelines has been investigated by Parker (2004) and Castello et al. (2005). For CH_4 Parker (2004) uses data from the OGJ annual Pipeline Economics report over the period 1991–2003, as we did in Section 2.1. The total cost of H_2 pipeline construction is determined by the application of correction factors to each of the individual cost components. Castello et al. (2005) determine for CH_4 the dependency of total construction costs on the pipeline diameter, by performing a regression analysis on a set of 26 cost data over the period 1990–1995. The pipeline cost conversion from CH_4 to H_2 is performed through the application of a diameter-dependent correction factor that accounts for additional cost requirements for H_2 pipelines, e.g. induced by improved welding and joining procedures, as well as different internal linings and coatings.

We use the models by Parker (2004) and Castello et al. (2005) to determine the costs per km of a 30 cm diameter H_2 pipeline. These authors do not indicate the precise date at which their data were published, but only report the period over which the data were collected. For Parker (2004) this time frame is 1990–2002 and for Castello et al. (2005) 1988–1999. We correct for inflation from the middle of the time periods considered – 1996 for Parker (2004) and 1993 for Castello et al. (2005) – with respect to our base year 2000. The resulting cost breakdown, as based on the model by Parker (2004), is shown in Table 4. The cost model of Castello et al. (2005) results in a total H_2 pipeline construction cost of as much as 1129 kUS$(2000)/km. The large deviation, of about 32%, between these two models is probably caused by different methods to correct for additional costs for several components of H_2 pipelines with respect to more conventional pipelines. Also fluctuations like those reported for CH_4 pipeline right-of way fees may contribute to the observed discrepancy here.

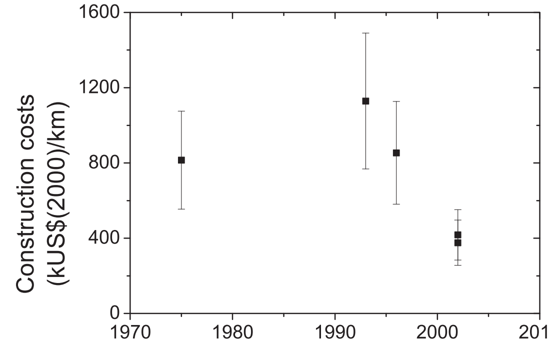

Fig. 5. Construction costs for 30 cm diameter H_2 pipelines.

Direct data on H_2 pipeline construction costs are generally scarce. We found data from four sources (Bogers et al., 1975; Castello et al., 2005; Mintz et al., 2002; Parker, 2004) in which costs are reported over the period 1975–2002 in US$, except for Bogers et al. (1975), which reports in Dutch guilders. In the latter case, we convert guilders first to US$(1975) before performing an inflation correction. These construction costs do not include extra charges to accommodate for special terrain or location conditions. The resulting numbers for H_2 pipeline construction costs are plotted against time in Fig. 5. We use the difference of 32% between the model of Parker (2004) and Castello et al. (2005) as error margin for these cost data.

4.2. Cumulative pipeline construction

The construction of H_2 transmission pipelines started in 1938 in the German Rhein-Ruhr area. This pipeline is still operational today. Since then an estimated 1600 km of H_2 pipelines have been built in Europe, and about 800 km in the US (Perrin et al., 2007). In Fig. 6 we show the historic development of the cumulative length of H_2 pipelines based on all major pipelines constructed in Canada, Europe and the US between 1938 and today (AFH, 2001; Perrin et al., 2007; Töpler, 2006; Vinjamuri, 2004). Fig. 6 accounts for essentially all H_2 pipelines constructed globally, and thus serves as good proxy for the overall experience gained in this domain. We think that the market for pipelines is global, so that possible learning effects are likely to spill over from one region of construction to another. Hence, in principle the information provided in Fig. 6

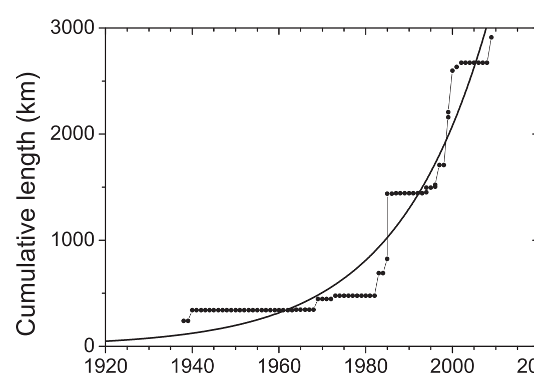

Fig. 6. Global cumulative length of H_2 pipelines constructed since 1938.

constitutes the proper basis for determining a world-wide learning curve for the construction of H_2 pipelines. We here do not discriminate between different pipeline diameters, construction materials or terrain conditions. We thus introduce an error in our analysis, but assume that the effect is small. Pipelines are often constructed in distinct modular parts, and are frequently extended after the first section has been made operational. As we only record pipeline construction after they have reached their full length, this practice causes jumps in the plot for cumulative installed pipeline length. We smoothen this graph by fitting the data with an exponential growth function, the solid line in Fig. 6.

The total pipeline length we find for Europe is 1639 km and for the US and Canada combined 1274 km. Our European figure agrees well with the estimate by Perrin et al. (2007). Our estimate for North America, however, is somewhat higher than their quote, even when we add to the latter the 240 km of pipeline constructed in the Mexican Gulf Coast area in 2009 and the 10 km built recently in Canada, both not included in their number. Based on a comparison of our results with those of Perrin et al. (2007) we estimate an error margin of 9% for the global cumulatively installed H_2 pipeline length. Apart from an 80 km H_2 pipeline in South Africa (Vinjamuri, 2004), a 13 km pipeline in Thailand and an 8 km pipeline in Brazil (AFH, 2001), we found no other significant stretches of H_2 pipelines in the world. We have not included the latter three pipelines in Fig. 6, because we have no reliable information on when their operation started. This omission hardly affects our results, since their contribution to the total of 2900 km of cumulative constructed pipeline length falls well within our standard deviation of 9% and can thus be neglected. Fig. 6 thus covers the vast majority of H_2 transmission pipelines constructed globally.

5. Learning behavior of pipeline construction

We have pointed out that over the past three to four decades no reductions can be observed for CH_4 pipeline construction costs. Rather, these costs prove to be too volatile to distinguish any long-term (decreasing or increasing) cost trends, but strongly follow short-term market price or cost component developments. There is also a lack of data on the evolution of cumulative CH_4 pipeline length, both regionally and globally. These factors prevent us from determining a (regional or global) learning curve for CH_4 pipeline construction activity.

We hereby confirm that technologies exist that display no or little learning-by-doing, as argued by Sagar and van der Zwaan (2006). Or at least, learning may be hard to observe, even if in reality such phenomena may be present. In the case of CH_4 pipeline costs, we think no learning curves can be determined – unlike prematurely claimed by Zhao and Schrattenholzer (2000) – mainly because of a lack of appropriate cost and capacity data for early deployment. One of the underlying reasons is that pipelining activity goes back as far as a century. Another explanation may be that in fact pipeline construction has hardly ever been subject to substantial learning, given that the technology at its core is rather rudimentary. There may always have been little scope for technical or labor-related improvements – if at all, cost reductions may have mostly derived from optimizing procedures such as the acquisition of licensing.

The construction costs we gathered, as plotted in Fig. 4, proved to be too volatile to allow discerning any overall cost trend. Hence, we are unable to determine a learning curve for CO_2 pipeline construction activity. The exceptionally large scattering of construction costs completely prevents us from making a fit of cost-versus-capacity data. Like for CH_4, we thus conclude that no effect of learning-by-doing is observable, and perhaps even present, for the construction of CO_2 pipelines.

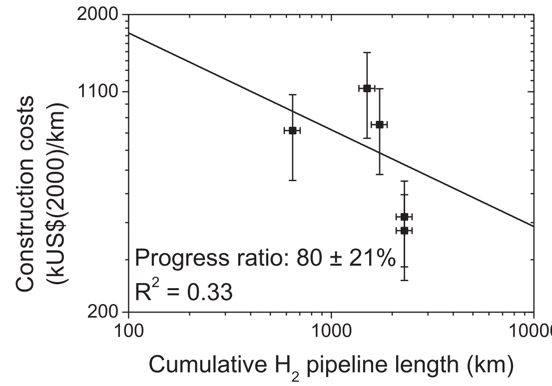

Fig. 7. Learning curve for the construction costs of 30 cm diameter H_2 pipelines. Data from various sources.

For H_2 pipeline costs our attempt to develop a learning curve looks more promising, since not only were we able to determine the evolution of cumulative pipeline length to date, but we also gathered a data set depicting reasonably well a cost reduction over about three decades of experience with H_2 pipeline construction. We combine the cost data from Fig. 5 with the fit of cumulative capacity from Fig. 6 and plot the result in Fig. 7 on a double logarithmic scale. We make a regression of the data points with a power law using a least squares fitting procedure (for the details and relations regarding the construction of a learning curve, as well as a recent example, see e.g. Schoots et al., 2010). As can be seen, we observe some learning effect, with a progress ratio of 80%. The result is statistically little significant, however, as can be seen from the high standard deviation ($\sigma = 21\%$) and low correlation coefficient ($R^2 = 0.33$).

The reason for this fit being unreliable is of course the minor increase observed in cumulative length and the scarcity of available cost data on H_2 pipelines. For the development of a proper learning curve, an analyst needs data over at least two orders of magnitude of accumulated capacity (Ferioli et al., 2009). In our case the cumulatively installed length of constructed H_2 pipelines increased by only about one order of magnitude over the period for which we were able to retrieve cost figures. On the basis of Fig. 7 we carefully conclude that perhaps the beginning of modest learning effects can be detected for H_2 pipeline construction activity, although the five data points for the corresponding costs shown here do not justify any firm conclusions. We thus argue that only in an optimistic scenario we may observe some learning for H_2 pipeline manufacturing in the future, with a learning rate of around 20%. The uncertainty in this prediction, however, is large.

We see from the above that data on possible cost reductions for CH_4, CO_2 and H_2 pipeline construction activity, if at all present, are either too scattered or cover an insufficient range of cumulative pipeline length to determine a reliable learning curve. A general point for consideration is that the cost per km/cm of a pipeline is not a true indicator of the cost per unit energy or mass transported by a pipeline system. There may have been significant learning in the design, construction and operation of pipelines systems which may have led to higher upfront investment costs, but lower levelized costs per unit of energy or mass transported. Items which can be considered as potential areas where learning may have occurred are:

1. The use of flow coatings to increase flow speed and thus specific pipeline capacity
2. The use of supercritical conditions to enhance specific pipeline capacity

Table 5
Onshore pipeline construction costs and their bandwidths.

Gas transported	Cumulative length in 2003 (km)	Construction costs (kUS$(2000)/km)	Construction cost bandwidth (kUS$(2000)/km)
CH_4	n.a.	715	228–1807
CO_2	4200	788	113–2767
H_2	2400	854	376–1129

3. An increased use of gas storage facilities to smoothen out peak flow variations
4. The development of more efficient compressors
5. The connection of pipelines into loops combined with the addition of compression stations to better match investment costs with capacity development
6. The use of advanced mapping to optimize pipeline routes
7. Reusing existing pipelines, also those originally meant for transporting other media
8. Advanced inspection techniques to improve the pipeline lifetime and reduce its maintenance costs
9. Improvements in long-term forecasting of future demand for energy and mass transport capacity on a pipeline route to reduce the investments in overcapacity.

The large observed volatility of the data we gathered invites making an overview of the approximate bandwidths over which pipeline construction costs may fluctuate for onshore CH_4, CO_2 and H_2 transportation, which we do in Table 5. Whereas our cost data suggest that onshore pipeline construction costs do not show the cost-reducing effects normally associated with learning-by-doing – or at least the data are too scarce, incomplete and/or scattered to discern any firm cost reduction trend – pipeline construction costs prove far from constant. The typical bandwidth of reported cost data, i.e. the range between the lowest and highest reported construction cost figures, as indicated in the right column of Table 5, is large. What are the reasons behind these large bandwidths and do they explain the limited learning effects we observe?

Differences in pipeline design requirements are set by the flow speed, operating pressure, Maximum Operating Pressure (MOP) as well as the chemical properties of the gases transported. These factors inevitably cause fluctuations in the construction costs between projects, which may be enhanced by varying safety regulations across different countries. In this paper we partially circumvent this problem by differentiating between three different gases – CH_4, H_2 and CO_2. Our efforts to determine learning curves for pipeline construction for each of these products separately still prove unsuccessful. Among the reasons are that we could not retrieve detailed information on the specific materials used and the applied wall thicknesses of the pipelines, which would have improved and refined our analysis. Another important cause for fluctuations in construction costs is, as we demonstrated, the different terrains distinct pipelines may run through.

The situation of almost every new pipeline project is unique and different from its predecessors. All the above aspects have thus to be evaluated on a project-to-project basis. As a result, it is hard or even impossible to determine one universal value for total pipeline construction costs that is applicable in all places and under all conditions. Because each pipeline construction project has its own specific set of engineering challenges, at least part of the experience obtained in previous pipeline construction projects cannot be used for the next. Learning-by-doing has therefore intrinsically limited impact on onshore pipeline construction development.

Onshore pipeline construction has by now fully developed into a mature technology. Although under some circumstances future construction projects may still be subject to new challenges that need to be surmounted, the technology seems to have entered a stage in which most possibilities for further optimization and cost reductions have been exploited. Market price fluctuations of the pipeline's construction materials, as well as differences between local labor and right-of-way costs, dominate over possible remaining cost reductions through learning effects. In fact, these factors may well cause increases in the total costs for future pipeline projects.

Reliability, health, safety and environmental requirements have become more stringent over time, and may increasingly do so in more countries in the world, so that national and regional differences may gradually converge (Kramer, 2009). These three requirements have over the past decades clearly added to overall costs, rather than reducing them. The cost of flue-gas desulphurization in power plants, for example, where early specifications were improved with a resultant increase rather than decrease in costs. Increasingly stringent safety requirements for nuclear power plants led to increasing costs for nuclear power. Similar effects have also been found for the costs of centralized large-scale H_2 production (Schoots et al., 2008).

Ferioli and van der Zwaan (2009) demonstrate that learning effects can quite generally only be expected during a limited amount of time, and typically only during the early stage of technology development. In particular, the maturity of pipeline construction technology suggests that significant future cost reductions through learning-by-doing are no longer very likely. The construction of H_2 pipelines is a somewhat newer industrial activity. In several respects it is different from CO_2 pipeline construction, which in turn differs somewhat from the construction of CH_4 pipelines. For H_2 pipeline construction some learning effects may still be possible. But probably more importantly, the market price for steel, labor costs and right-of-way fees may be more determinant – and go either down or up, or both during different points in time. Economies-of-scale effects may perhaps still have some beneficial effects on H_2 pipeline construction costs. A similar argument can probably be made for operation and maintenance: also for the costs associated with these onshore pipeline activities no significant learning effects are to be expected, but cost reductions may still take place through other phenomena.

6. Summary and conclusion

Table 6 summarizes the breakdown of construction costs for 30 cm diameter onshore pipelines that transport CH_4, CO_2 and H_2, as reported, respectively, in Sections 2.1, 3.1 and 4.1. As can be seen, the total construction costs are lowest for CH_4 and highest for H_2 pipelines. The absence of major steel degradation problems for CH_4 pipelines is the main reason that material costs for the transportation of this gas can be kept relatively low. The chemical and physical properties of CO_2 and H_2 demand for special material requirements for these pipelines. Table 6 thus shows higher material costs for pipelining CO_2 and H_2 in comparison to that of CH_4. Pipelines for fluids, like CO_2 at a pressure above 74 bar, may be as easy to construct as those for CH_4, which explains why the corresponding labor costs are roughly equal. The volatility of H_2, however, requires

Table 6
Breakdown of 30 cm onshore CH_4, CO_2 and H_2 pipeline costs.

Cost component	CH_4 (kUS$(2000)/km)	CO_2 (kUS$(2000)/km)	H_2 (kUS$(2000)/km)
Materials	89	187	143
Labor	363	358	463
Right-of-way	67	44	69
Miscellaneous	196	199	179
Total	715	788	854

additional measures to prevent leakage, such as improved welding and joining procedures. These extra procedures imply an increase in labor costs in comparison to the construction of pipelines for the other two gases.

As argued in Section 5, we may rather safely conclude that limited learning effects can be observed for onshore pipeline construction costs. As a result, and given the maturity of the technology, we do not expect significant cost reductions from learning-by-doing effects for the near-term future. This also applies to locations where limited knowledge on pipeline construction is present. Knowledge acquired from abroad will be incorporated fast and only a limited, short-term learning effect may be observable. An important conclusion that follows from our component-based analysis of pipeline construction costs is that, instead, total pipeline costs for each of the three gases that we inspected tend to closely follow the market price of the necessary material inputs, totally in line with the arguments by Ferioli et al. (2009). The overall costs are also strongly determined by several other cost components, among which in particular, in decreasing order of importance, labor costs, miscellaneous contributions and right-of-way fees. We have showed the workings of these respective cost contributions for CH_4 pipeline construction in detail. For the other two gases the total pipeline costs depend similarly on the costs of these components.

This paper may provide a prelude to possible further work on the financing of CO_2 and H_2 pipeline infrastructure. Future work may elaborate further on issues such as:

1. The context of pipeline investment uncertainties. Such a study may take shape by quantifying how the uncertainty in required pipeline investment compares with other uncertainties in the costs of decarbonising the economy.
2. The impact of geographic factors. In this paper we averaged these factors out by considering a large number of pipelines. If the cost data were combined with geographic data, e.g. in GIS format, this could provide more detailed insight in the effect that different terrains have on pipeline construction costs.
3. The impact of the volatility in pipeline cost on past investment decisions. Research may focus on whether investors had sufficient foresight to factor higher costs into their financing and levelized cost models or whether insufficient insight led to sub-optimal pipeline projects.
4. The extent by which long time periods and large geographic distance between pipeline projects may partially or completely cancel cost reductions from learning-by-doing.
5. The drivers and variation of other cost components of the levelized costs such as pipeline lifetimes, annual operating and maintenance costs, and lead times for CH_4, CO_2 and H_2 pipelines.

Acknowledgements

This research was funded by the Netherlands Organization for Scientific Research (NWO) under the ACTS Sustainable Hydrogen program (nos. 053.61.305 and 053.61.024) and made possible through the Technical University of Eindhoven, The Netherlands. The authors would like to acknowledge Heleen Groenenberg, Chris Hendriks, Gert Jan Kramer and Erika de Visser and two anonymous reviewers for providing us with data and feedback that has significantly improved the quality of our analysis. They are also grateful to many colleagues in the ACTS program and at ECN for useful comments during the presentation of the findings reported in this article. The authors are responsible for all remaining errors.

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