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

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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

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[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.

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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.

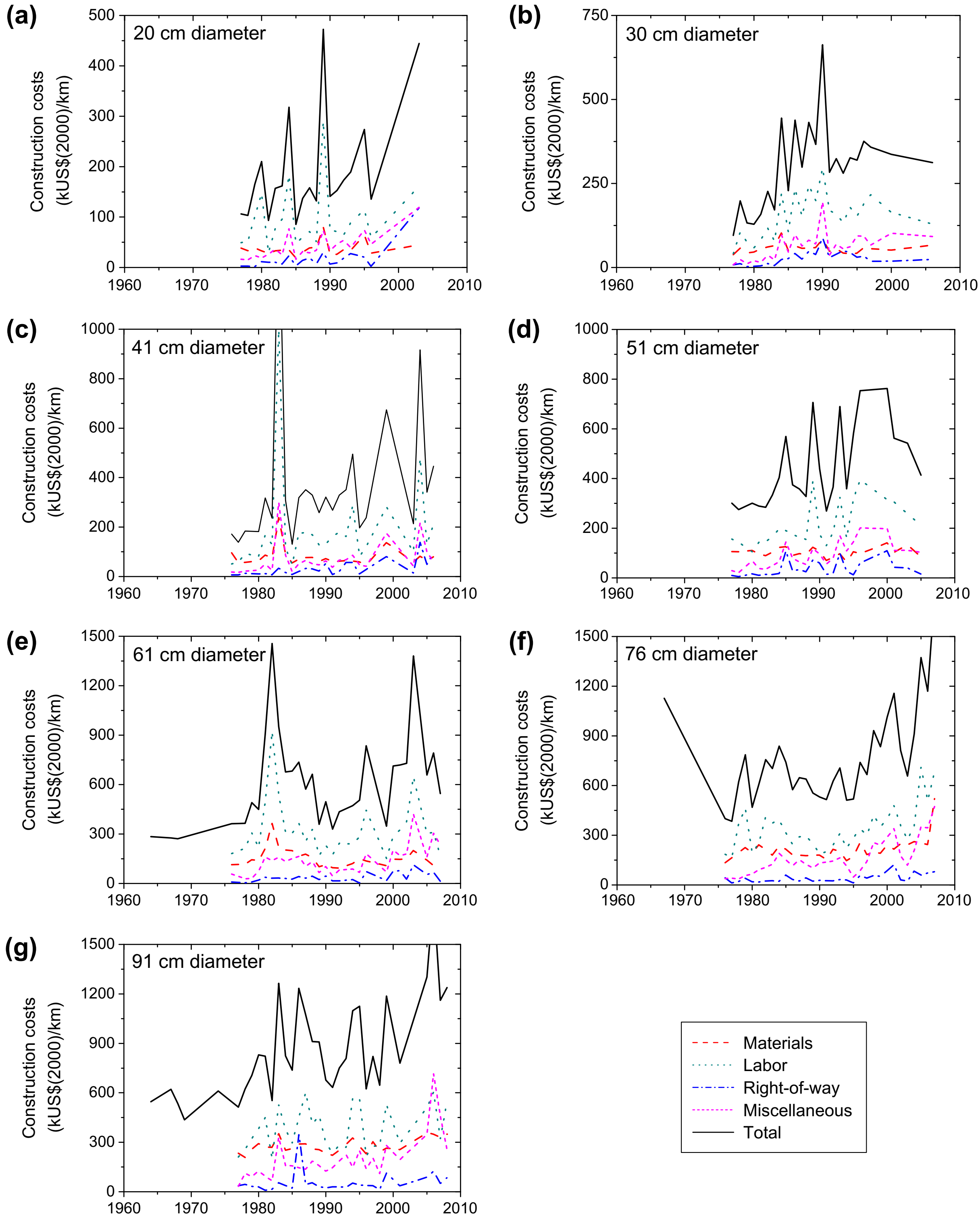

Fig. 1. Construction costs of onshore CH_4 pipelines between 1985 and 1998. Data from Gasunie and OGJ.

Technical difficulties associated with the placement of pipelines in lesser accessible terrain typically cause costs to rise [31]. 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 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, costs should be increased by 10–50% with respect to costs on grassland.

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. Correction factors for countries and regions to account for these location variabilities may vary between 0.7 and 1.2 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 results, which demonstrate the relative size of each of the four main cost shares. As one may expect, the total costs for pipeline construction, indicated below each pie diagram, increase with pipeline diameter. Fig. 3 suggests 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$/km reported by Parker [30], and deviate by about 10% from the 786 kUS$/km level reported by Castello et al. [26], both for 30 cm diameter pipelines. This 10% discrepancy is used as error margin in Fig. 3. A clearly observable trend is that 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.

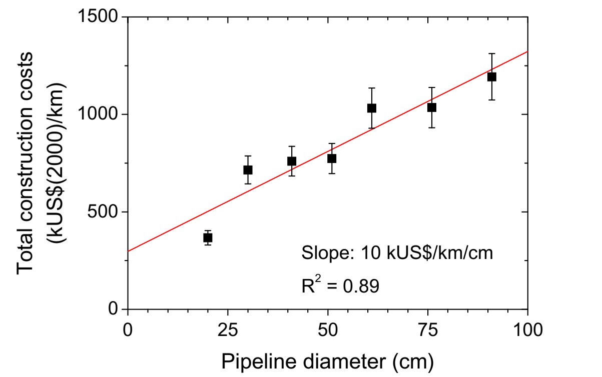

Fig. 3. CH_4 pipeline construction costs versus diameter with cost data from Fig. 2 and a linear fit by the authors.

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

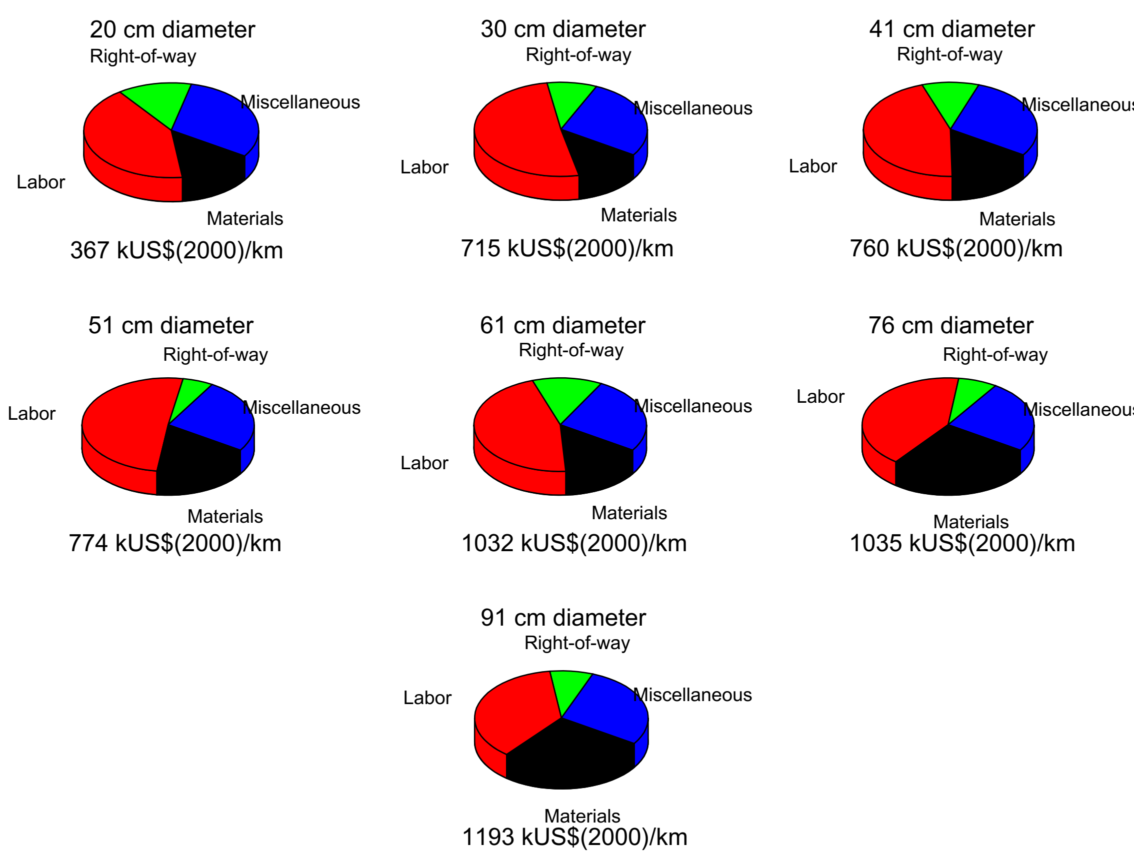

Fig. 2. Average cost breakdown for CH_4 pipeline construction between 1998 and 2008. Data from Gasunie and OGJ.

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. 4a–d.

The material cost index is compared with the Producer Price Index (PPI) for iron and steel [65]. 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. 4a, 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. As can be seen from Fig. 4b, 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 [33]. 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. 4c, particularly during the last decade. Overall, however, we 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 [34]. 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

The annual oil and gas surveys published in OGJ also include the total mileage of CH_4 pipelines in operation in the US, as well as the length and diameter of additional pipelines constructed every year. The evolution of this total and the annually added mileage is shown in Fig. 5. Annual additions are discernable in the total figure for operational pipeline length, but the mileage decommissioned during the first half of the 1990s is much larger: while the former typically account for percentage level increases, the latter amounts to a decrease in total pipeline mileage of approximately 30%. The gas consumption figures over this period do not reflect this sudden drop in pipeline mileage. It is therefore unlikely that the 30% decrease can be attributed to decommissioning of pipelines. The

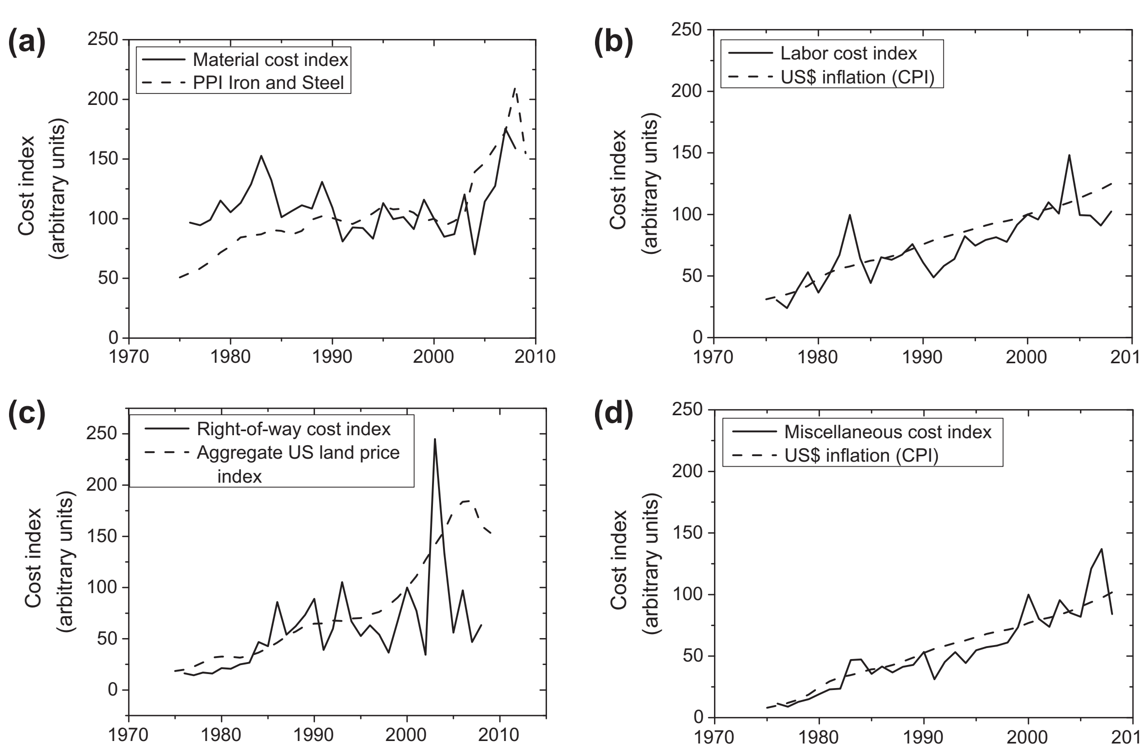

Fig. 4. CH_4 pipeline construction cost component indices (solid lines) matched with price indices (dashed lines): US Producer Price Index for iron and steel for (a), US consumer price index for (b and d) and US aggregate land price index for (c).

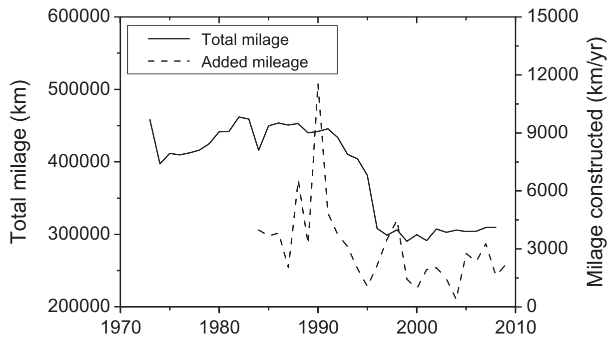

Fig. 5. Total mileage of CH_4 pipelines in operation and additional mileage constructed annually in the US.

OGJ reports only published data from pipelines registered by the US Federal Energy Regulatory Commission (FERC). In 1984 FERC changed its definition to only account for pipelines owned by major companies. This change explains the slight fall in total mileage visible in 1984, but not the large decrease in the early 1990s. The latter decrease in pipeline mileage might have been caused by a deregulation of the pipeline sector, which started in the 1980s and concluded mid-1990s. It may have caused changes in the ownership or status of a large share of the pipeline infrastructure such that about 30% fell outside the requirements to be included in the FERC statistics. Unfortunately, the OGJ data do not fully match with figures reported elsewhere. For example, Castello et al. [26] claim that by the end of 2003 1750000 km of pipeline existed in the US, of which 525000 km were transmission pipelines; OGJ reports only 303000 km. We presume that this discrepancy partly results from a difference in pipeline sizes included in these respective publications: Castello et al. [26] include all sizes down to 10 cm, while OGJ reports pipelines with diameters between 5 and 107 cm but only owned by enterprises defined as 'major company'. The difference may also derive from variable assumptions regarding the operational status of pipelines in these respective statistics.

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 – on the basis of the data depicted in Fig. 5 alone – reconstruct a reliable value for the cumulative length of deployed CH_4 pipelines in the US. 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. In practice, extra measures like the application of protective layers are required (accompanied with an additional price tag) to prevent the quality of the pipeline metals from deteriorating too quickly.

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 in protected or closed spaces with limited air circulation. Seepage of CO_2 involves risks of suffocation for animals and humans. Along CO_2 pipelines, sensors are thus required to detect possible leakage in view of avoiding casualties. 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.

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 Refs. [32,35–44]. 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 diameter dependency of CH_4 pipeline costs depicted in Fig. 3. We correct data for currency and inflation effects so as to obtain costs expressed in US$(2000)/km. The result is shown in Fig. 6. 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. 6 can thus be attributed to widely diverging characteristics of individual pipeline projects, such as related to terrain, country, right-of-way, permitting and regulation. Note that safety regulation for CO_2 transport across planes in the USA is limited: more stringent regulations in more densely populated areas would imply higher costs.

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. 6 – 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 [44]. We apply their cost share calculations (based on a methodology similar to the one in Parker [30] but applied to CO_2 pipelines) to our central mean, the result of which is shown in Table 1.

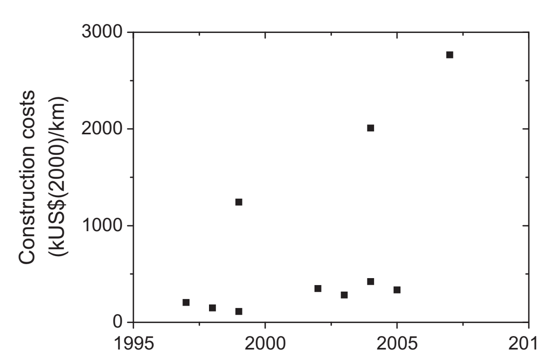

Fig. 6. Construction costs for 30 cm diameter CO_2 pipelines.

Table 1
Construction cost breakdown for a 30 cm diameter CO_2 pipeline.

Component	Cost share (%)
Materials	24
Labor	45
Right-of-way	6
Miscellaneous	25
Total mean (in kUS$(2000)/km, without terrain)	788

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 [43,45]. 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 [40,43,46–49]. 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 [40]. 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 [46,50]. The Dutch NPM oil pipeline built in 1969 between Rotterdam Botlek and Amsterdam West is now used to transport CO_2 to greenhouses [51,52].

The evolution of cumulative pipeline length is plotted in Fig. 7. For some pipelines we only know roughly the period in which they came into operation. For these cases we take the last year of the interval as the time of construction. The jumps visible in Fig. 7 largely originate from this assumption – in reality this graph would presumably look less bumpy. To get a smoother and more accurate representation of the cumulative pipeline length development over time we regress the data with an exponential function (including an offset) through a least-square fitting procedure. The result, shown as solid line in Fig. 7, is nearly a straight relationship.

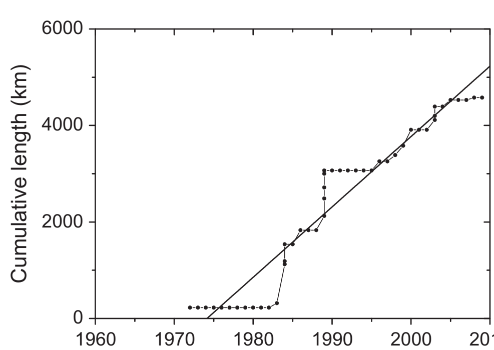

Fig. 7. Global cumulative CO_2 pipeline length since the 1970s.

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% [31].

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 [26,31]. 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 the need for booster stations along the pipeline [26].

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 [30] and Castello et al. [26]. For CH_4 Parker [30] 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. [26] 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 [30] and Castello et al. [26] 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 [30] this time frame is 1990–2002 and for Castello et al. [26] 1988–1999. We correct for inflation from the middle of the time periods considered – 1996 for Parker [30] and 1993 for Castello et al. [26] – with respect to our base year 2000. The resulting cost breakdown, as based on the model by Parker [30], is shown in Table 2. The cost model of Castello et al. [26] 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.

Direct data on H_2 pipeline construction costs are generally scarce. We found data from four sources [26,30,53,54] in which costs are reported over the period 1975–2002 in US$, except for Bogers et al. [53], which reports in Dutch guilders. In the latter case, we convert guilders first to US$(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. 8. We use the difference of 32% between the model of Parker [30] and Castello et al. [26] 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 [55]. In Fig. 9 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 [55–58]. Fig. 9 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. 9 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. 9.

Table 2
Construction cost breakdown for a 30 cm diameter H_2 pipeline.

Component	Cost share (%)
Materials	17
Labor	54
Right-of-way	8
Miscellaneous	21
Total mean (in kUS$(2000)/km, without terrain)	854

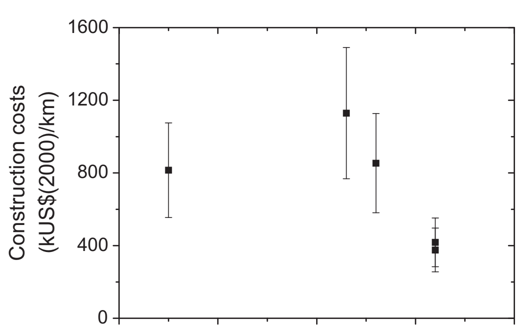

Fig. 8. Construction costs for 30 cm diameter H_2 pipelines.

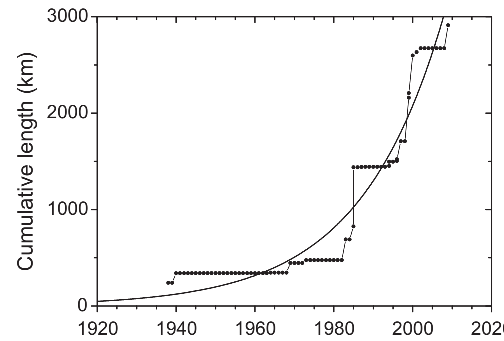

Fig. 9. Global cumulative length of H_2 pipelines constructed since 1938.

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. [55]. 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. [55] 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 [58], a 13 km pipeline in Thailand and an 8 km pipeline in Brazil [56], we found no other significant stretches of H_2 pipelines in the world. We have not included the latter three pipelines in Fig. 9, 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. 9 thus covers the vast majority of H_2 transmission pipelines constructed globally.

5. Learning behavior of pipeline construction

Over the past three to four decades no reductions can be observed for CH_4 pipeline construction costs. Rather, as we have pointed out, 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 [59]. 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 [60] – 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.

Even while for CO_2 we were able to determine the evolution of cumulative pipeline length to date, as shown by the graph in Fig. 7, the construction costs we gathered, as plotted in Fig. 6, 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.

For H_2 pipeline costs our attempt to develop a learning curve looks a little 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. 8 with the fit of cumulative capacity from Fig. 9 and plot the result in Fig. 10 on a double logarithmic scale. We make a regression of the data points with a power law using a least squares fitting procedure. 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 (σ = 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, data are needed over at least two orders of magnitude of accumulated capacity [61]. 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. 10 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.

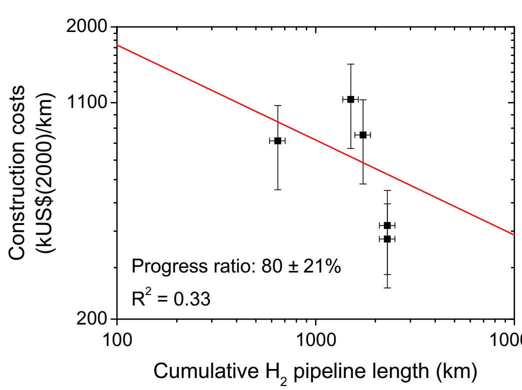

Fig. 10. Learning curve for the construction costs of 30 cm diameter H_2 pipelines. Data from various sources.

Table 3
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

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. 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 3. 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 3, is large. These bandwidths explain to a large extent why we observe no or limited learning effects.

6. Summary and conclusion

Table 4 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 4 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 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 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 any significant cost reductions from learning-by-doing effects for the near or longer-term future. This also applies to locations where limited knowledge on pipeline construction is present. Knowledge acquired from abroad will be incorporated fast and

Table 4
Breakdown of 30 cm onshore CH_4, CO_2 and H_2 pipeline costs (with relative cost shares in brackets).

Cost component	CH_4 (kUS$(2000)/km)	CO_2 (kUS$(2000)/km)	H_2 (kUS$(2000)/km)
Materials	89 (12%)	187 (24%)	143 (17%)
Labor	363 (51%)	358 (45%)	463 (54%)
Right-of-way	67 (9%)	44 (6%)	69 (8%)
Miscellaneous	196 (27%)	199 (25%)	179 (21%)
Total	715	788	854

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. [61]. 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.

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Appendix A. Learning curve methodology

For decades learning curves have been used as a suitable visualization of learning-by-doing. Learning curves express the hypothesis that the costs of a technology decrease by a constant fraction with every doubling of cumulative installed capacity or exercised activity. Hence, on a double-logarithmic scale a plot with technology costs versus cumulated manufacturing or usage involves a downward sloping straight line. In other words, technology costs follow the relation:

$$c_t = c_i\left(\frac{P_t}{P_i}\right)^{-\alpha}, \quad (1)$$

in which c_t is the cost of the technology at time t, c_i its initial cost (in principle per item of the first batch of production), P_t the cumulative production at time t, P_i the initial cumulative number of produced items (normally but not necessarily in the first batch of production) and α the learning index. The learning index is related to the progress ratio pr via the relation $pr = 2^{-\alpha}$. The learning ratio, $lr = 1 - pr$, expresses (usually in percentages) the relative cost reduction after each doubling in cumulative capacity. In the present study we use, like others in similar publications on learning curves for different (energy) technologies, data available from the open literature, since in-house company information is often kept confidential. The phenomenon of learning curves has been extensively explained in more detail in scores of publications, among which notably OECD/IEA [62]. Efforts to unpack learning-by-doing include most recently, for example, Ferioli et al. [63].

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