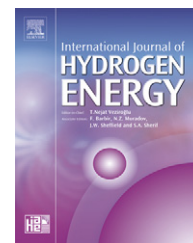


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Learning curves for hydrogen production technology: An assessment of observed cost reductions

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ABSTRACT

At present three key energy carriers have the potential to allow a transition towards a sustainable energy system: electricity, biofuels and hydrogen. All three offer great opportunity, but equally true is that each is limited in different ways. In this article we focus on the latter and develop learning curves using cost data observed during the period 1940–2007 for two essential constituents of a possible ‘hydrogen economy’: the construction of hydrogen production facilities and the production process of hydrogen with these facilities. Three hydrogen production methods are examined, in decreasing order of importance with regards to their current market share: steam methane reforming, coal gasification and electrolysis of water. The fact that we have to include data in our analysis that go far back in time, as well as the uncertainties that especially the older data are characterized by, render the development of reliable learning curves challenging. We find only limited learning at best in a couple of cases, and no cost reductions can be detected for the overall hydrogen production process. Of the six activities investigated, statistically meaningful learning curves can only be determined for the investment costs required for the construction of steam methane reforming facilities, with a learning rate of $11 \pm 6\%$, and water electrolysis equipment, with a learning rate of $18 \pm 13\%$. For past coal gasification facility construction costs no learning rate can be discerned. The learning rates calculated for steam methane reforming and water electrolysis equipment construction costs have large error margins, but lie well in the range of the learning reported in the literature for other technologies in the energy sector.

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1. Introduction

Recently, hydrogen has gained considerable interest as potential alternative fuel for zero-emission vehicles. Compared to the direct use in the transport sector of fossil fuels like oil and natural gas, however, the costs associated with the use of hydrogen are high at present. The overall costs of hydrogen usage can be split into four main components: production costs,

distribution costs, storage costs and costs of end-use in, for example, fuel cells. In this paper we focus on the former, and present an analysis of hydrogen production cost reductions as achieved over approximately the past six decades. These observed cost reductions can be instructive for assessing the possibility of realizing hydrogen production cost improvements in the future and may provide an indication for the viability of establishing a hydrogen economy.

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We base our analysis on open literature data (as opposed to confidential company data). The costs we report below may be biased towards the lower end, because open literature cost data do regularly not report a variety of additional costs e.g. as related to the installation phase of hydrogen plants. Hydrogen can be produced through a number of different methods. In this paper we investigate three such techniques: steam methane reforming (SMR), electrolysis of water and coal gasification. Although we also addressed another important hydrogen production technology, the partial oxidation of heavy oil, we have not been able to retrieve enough reliable annual production data for this technique to independently determine the evolution of its employment over time; so we have discarded this alternative from our study. One of the possible explanations for the lack of production data for partial oxidation is the wide variety in feedstock for this technology. Also, quoted figures on hydrogen production through partial oxidation of heavy oil are sometimes diluted with amounts of hydrogen produced via the partial oxidation of natural gas, and the purity of the syngas produced by partial oxidation is not rarely left unrevealed, which leads to sizeable uncertainties in the precise amount of hydrogen produced via this method. These are additional reasons for not reporting on partial oxidation hydrogen production in this paper. The contributions of each of the other three main methods to their sum, in terms of both hydrogen production capacity and the global amounts of hydrogen produced, are shown in Figs. 1(a) and (b), respectively, as function of time since the origin of industrial hydrogen production.¹ The curves in these figures have been plotted with the assumption that the partial oxidation of heavy oil accounts for approximately 30% of the total of all methods combined, both for the global production capacity and for the amount of hydrogen produced.²

As the cumulative installed hydrogen production capacity increases, experience is obtained in both building production facilities and producing hydrogen with these facilities. The energy policy literature extensively reports that for many technologies these types of activities have resulted in (sometimes impressive) cost reductions. The observed relation between such cost reductions and the experience accumulated through deployment or employment activity is normally referred to as “learning-by-doing”. The purposes of this article are to explore the existence of this learning phenomenon for hydrogen production technology and determine whether hydrogen production cost targets are achievable in the near future. The US Department of Energy target for the year 2017 for hydrogen fuel production costs from SMR is 2.00

US\$ per gallon of gasoline equivalent (gge) and for electrolysis 3.00 US\$ per gge. In both cases the production cost targets do not include taxes but do contain a cost target of 1.00 US\$ per gge for delivery at the pump [3]. In terms of the hydrogen higher heating value (HHV), the production part (excluding taxes and delivery) of the US Department of Energy targets for hydrogen production costs are 0.025 US\$/kWh for SMR and 0.05 US\$/kWh for electrolysis.³

For many decades already, 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 installed capacity or exercised activity. Hence, on a double logarithmic scale the relation between these technology costs and cumulated manufacturing or production involves a downward sloping straight line (see, for example, [4,5]). In 1936 the first learning curve was determined for the amount of labor hours spent on building aircraft [6]. Since then, analysts in commerce, consulting and academia have determined learning curves for a large range of industries and technologies.

Learning curves can be expressed as a power-law:

$$c_t = c_0 \left(\frac{P_t}{P_0} \right)^{-\alpha}, \quad (1)$$

where c_t is the cost of the technology under consideration at time t , c_0 in principle the cost per item in the first batch of production (the point in time at which this occurs usually being referred to as $t = 0$), P_t the cumulated production of items at time t , P_0 the number of items in the first batch of production at $t = 0$, and α the learning index. P can be dimensionless, when its values are obtained by simply counting items of a certain technology, or may be expressed in a variety of different units (like MW, MWh or GJ, in the energy sector). In this paper P_t is either the cumulated installed hydrogen production capacity (which we express in GW) or the cumulated amount of hydrogen produced (which we express in TWh) at time t . P_0 refers to, respectively, the installed hydrogen production capacity or the amount of hydrogen produced at our choice for $t = 0$.

The progress ratio pr expresses the fraction to which costs are reduced with every doubling of, in our case, either the cumulated production capacity or the cumulated amount of hydrogen produced, and is related to α by

$$pr = 2^{-\alpha}. \quad (2)$$

The progress ratio is related to the more commonly used learning rate, lr , through $lr = 1 - pr$, and is, like pr , usually expressed in percentages. Typical values for lr and pr are, for example, 20% and 80%, respectively.

In spite of extensive research efforts, the mechanisms behind cost reducing learning phenomena are still poorly understood (see notably [7–11]), even while several studies point out the direction of search and other analyses have booked some progress in opening the black box of learning-by-doing (e.g. [12–14]). In the present paper we attempt to further unpack this black box. Learning curves can, by

¹ The total figures and the shares of individual methods have been independently retrieved from various sources in the open literature. As a result, depending on the year under consideration, the production capacities/amounts of the different methods do not always add up to 100%, but rather to typically about 97%. This difference can be explained by a few remaining processes that have hydrogen as by-product. The hydrogen co-produced in chlorine production explains most of the observed discrepancy (3.6% in 1983 and 3.0% in 1998; see [1]).

² The partial oxidation share of 30% is adopted from [2] and refers in principle to 2003 only. For ease of exposition, we assume that this share also approximately applies to other years.

³ In this paper we use the HHV of hydrogen (39.41 kWh/kg). The US Department of Energy targets are based on the lower heating value (LHV) of hydrogen (33.33 kWh/kg).

definition, only be determined for technologies that have matured sufficiently, that is, deployed to such an extent that has allowed their relatively widespread commercialization. Naturally, learning curves cannot be determined for technologies that never reached this phase, but were pushed out of the market before reaching this stage of significant diffusion. Technological breakthroughs and the introduction or the withdrawal of government support for technologies are examples of events that may influence the progress ratio or the continuation of cost reductions. These are some of the reported reasons that an established progress ratio for a particular technology might not be guaranteed to hold for the future [14]. Hence, as is also discussed below, even for the cases in which one manages to derive learning curves, there is no certainty that similar cost reductions continue to apply in the future. The nature and amount of data available did not allow us to distinguish between learning-by-doing and learning-by-searching (R&D). In this study, these two phenomena are not separated. Irrespective of these caveats, however, the development of learning curves can shed light and provide valuable insight for energy technology policy making.

In this article we determine learning curves for hydrogen technology, by relating the investment costs required for the construction of hydrogen production facilities to their corresponding cumulated capacity. Likewise, we present learning curves expressing hydrogen production costs as function of the cumulative amount of hydrogen produced. The literature distinguishes between *learning curves* that are based on cost data, and *experience curves*, based on data for prices. Recently, Rubin et al. [15] proposed an experience curve for SMR. We here expand their work, first by extending the set of investigated hydrogen production technologies from not only SMR to also electrolysis of water and coal gasification. Second, we present an analysis complementary to that of Rubin et al. [15] by determining learning curves, rather than experience curves. The advantage is that learning curves are cost-based and thus less influenced by the fluctuation of market prices. To our knowledge, no learning curves have so far been reported for these three hydrogen production methods. Although we find little learning, we still publish these results, as we believe that too often results involving

little learning are left unreported. This unfairly shifts the picture in favor of learning at large.

In the next section we determine estimates for both the global hydrogen production capacity and the amounts of hydrogen produced worldwide between 1940 and 2007. Using these retrieved data, we can readily calculate figures for the cumulated hydrogen production capacity and the cumulative amount of hydrogen produced over approximately the past six decades. Through an extensive literature search we obtained investment costs required for building hydrogen production facilities, as well as the costs associated with producing hydrogen, over this time frame, that are reported in Section 3. The method we use for the necessary inflation corrections and currency conversions is also described in this section. In Section 4, we combine the results from Sections 2 and 3 to construct learning curves for both the costs of building hydrogen production facilities and the costs of producing hydrogen with these facilities. In Sections 5 and 6 we, respectively, discuss our results and conclude by briefly exploring the possible consequences of our findings for energy and hydrogen technology policy making.

2. Hydrogen production

2.1. Cumulated hydrogen production capacity

In order to derive a learning curve for the construction of hydrogen production facilities we first determine the cumulated production capacity as function of time. In Fig. 1 we saw that the production capacity is unevenly distributed over the main available technologies and is strongly biased towards SMR. The market shares of the individual production methods have also changed over time and are not always known with high precision. These observations have implications for the relative statistical availability and quality of cumulative capacity data and therefore influence our ability to determine learning curves.

Coal gasification dominated the production of hydrogen until the mid 1940s. As countries changed from coal-based to oil- and gas-based economies also the method for hydrogen production gradually changed from the commonly used coal

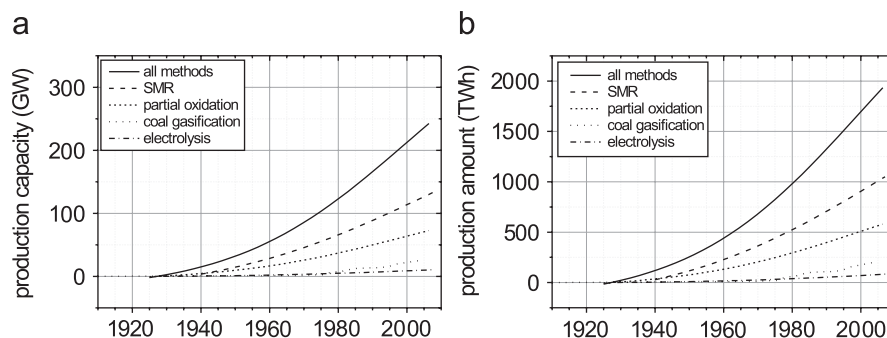


Fig. 1 – Comparison of the shares of different methods for (a) the global installed hydrogen production capacity and (b) the annual global amount of hydrogen produced. The data are from various sources (see below) and those for partial oxidation reflect the authors' assumption.

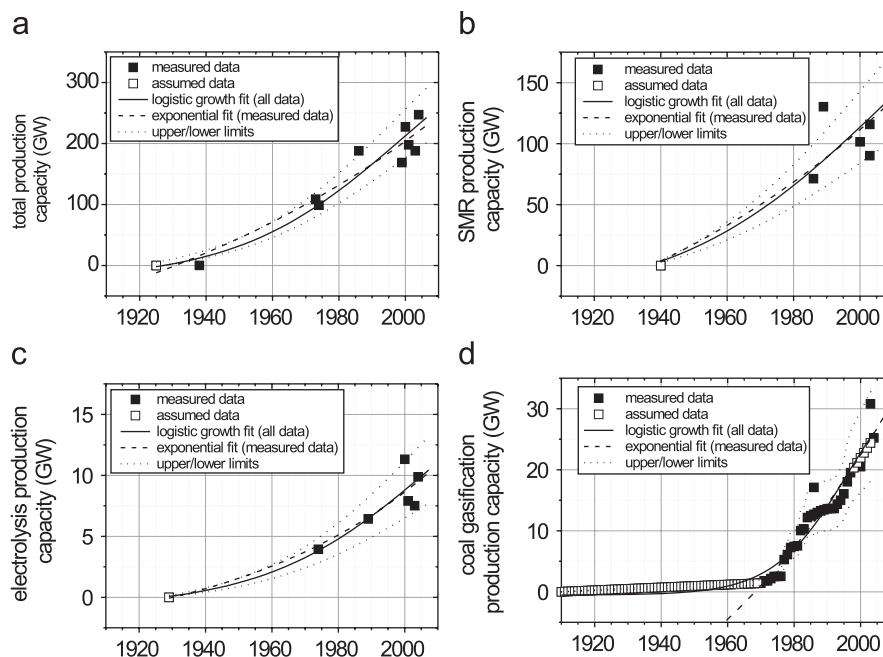


Fig. 2 – (a) Total global hydrogen production capacity and global production capacities for (b) SMR, (c) electrolysis of water and (d) coal gasification.

gasification to SMR and partial oxidation of oil and natural gas. Although some countries active in hydrogen production did not switch to oil and natural gas as fundamentally or rapidly as others, by 1989 about 75–80% of all hydrogen was produced from natural gas, liquefied petrol gas (LPG) and petroleum, 10–15% from heavy fuels, and only approximately 5% from coal and a similar contribution from electrolysis [16,17].⁴ Since the share of different feedstocks and methods for hydrogen production modified over time, we not just determine cumulated hydrogen production capacity figures for all methods combined, but also for each technology (or class of technologies) individually. For coal gasification, we managed to directly find data for global production capacities, but for SMR and electrolysis essentially all data available in the literature proved to be expressed in terms of annual amounts of hydrogen produced. Hence, for the latter two techniques, we converted the obtained data into numbers expressed in terms of production capacities. The literature sources from which we gathered all production capacity data and amounts of produced hydrogen are for the total hydrogen production over the period 1938–2004 [2,17,18,20,32,33], for SMR over the period 1986–2003 [2,18,20], for electrolysis over the period 1974–2004 [2,17,18] and for coal gasification over the period 1970–2004 [2,18–20].

The way in which we converted annual amounts of hydrogen produced to production capacities was through straightforward accounting for the load factor, defined as the average amount of time during which a plant is producing

hydrogen. The investigated literature sources show that over the period 1946–2004 the load factor was quite consistently about 91% subject to only relatively small changes [20–31]. The production capacities are thus on average a factor 100/91 larger than the annual amounts of produced hydrogen we found in the literature. The solid squares in Figs. 2(a)–(d) (referring to ‘measured data’, that is, reported in the open literature) show the total globally available hydrogen production capacity and the corresponding capacities for each individual production method, all as function of time. The open squares refer to data points we assumed for fitting purposes only. Installed global production capacities are expressed in GW, referring to the heat that would be generated per unit of time if the hydrogen produced was combusted.⁵

For the total production capacity and the capacities of SMR and electrolysis, considerable scattering can be observed in the data, as well as fairly large gaps in time between many of the single data points. Not surprisingly, much information on capacities exists for recent years, but reliable data from the early days of hydrogen production are scarce for all technologies. By fitting the hydrogen production capacity data shown in Figs. 2(a)–(d) with a growth function, we estimate the production capacities for the years where data points are missing. In order to generate a reasonable fit, we first

⁴ To give a sense of the uncertainties we encountered, other sources [2,18–20] report coal gasification contributing by about 8% to total global hydrogen production, hence significantly deviating from the share quoted here.

⁵ The reported figures are the HHV, so that 1 GW corresponds to approximately 220 kt H₂/yr. Both in terms of weight and volume, the HHV energy density of hydrogen strongly deviates from that of gasoline, by respectively a factor of 3.0 and 0.00033. Since we are mainly interested in hydrogen as energy carrier, we express all amounts of hydrogen in terms of their energy content rather than in physical quantities (weight or volume).

determine the year in which hydrogen production supposedly started. The element hydrogen was discovered in 1766, and the first use of a hydrogen production technology, the gasification of coal, dates back to as early as 1796. The earliest reported total installed global hydrogen production capacity amounted to 26 MW in 1938 [32]. We assume that, with significant variation depending on the production method employed, hydrogen production started on an industrial scale some time between 1910 and 1940.

We perform the fitting of the hydrogen production capacity data first with (the early stage of) a logistic growth function, i.e. an S-curve, since this function proves to properly reflect often observed market diffusion patterns (see e.g. [12]). In each of Figs. 2(a)–(d) this fit is shown as a solid line. The solid lines in Figs. 2(a)–(d) are only the first part of an S-curve, since there are no indications at present that the hydrogen production quantity might level off any time soon. We therefore assume that the installed hydrogen production capacity, at least for the near future, continues to grow at about the same pace as today and will only level off at some (unpredictable) point in a more distant future. The expectation by many that hydrogen becomes a pervasive energy carrier in decades from now strengthens this assumption. In Fig. 2(a) we have chosen 1925 (open square) as the supposed starting point for the installation of hydrogen production capacity, all methods combined. The open squares in Figs. 2(b)–(d) define the production starting points for SMR (1940), electrolysis (1929) and coal gasification (1910), based on their first application on an industrial scale [17,18].

The full evolution over time for the capacity of coal gasification was determined differently from the other cases, because the data we found for this method (mostly directly in terms of the installed global production capacity), as depicted in Fig. 2(d), were much more abundant than for SMR and electrolysis. The missing data points between 1910 and 1970, as well as 1997 and 2004, were reconstructed by linear extrapolation, respectively, interpolation, and are shown as open squares. The syngas produced by coal gasification, followed by a water-gas-shift reaction, contains a variable amount of hydrogen. For our purposes, we assume this syngas contains consistently 56% of hydrogen, 32% carbon monoxide and 11% methane. Fig. 2(d) only displays the share of hydrogen in the syngas generated from coal gasification.

A large spread exists in the production capacities reported in each of Figs. 2(a)–(d). This spread is most likely due to differences in the method applied by different authors to determine the underlying amounts of annually produced hydrogen. The spread can also be partly explained by different views on what may actually be counted as hydrogen production. Syngas, for example, does not have to be purified for the production of Fischer-Tropsch diesel. The quality of the produced syngas has probably changed over time. This causes an error in the determination of the hydrogen production capacity from coal gasification. We account for this spread by determining a theoretical upper and lower limit for the installed hydrogen production capacity, and assume that these limits are a constant factor off from the logistic growth fit. The offset factor is determined such that the literature data point most distant from the fit is just included

within the limits.⁶ The upper and lower limit serve as confidence levels for the logistic growth fits and are shown as dotted lines in Figs. 2(a)–(c). Because of the abundance of the coal gasification production capacity data in Fig. 2(d), we did not follow this procedure for finding the upper and lower limits for this case; here we were able to base uncertainty boundaries on a scaling with respect to the true data points, rather than on the fitted logistic growth curve.

In view of the possibility that the use of hydrogen expands massively over decades to come, it is not inconceivable that the production of hydrogen grows at a continually increasing speed at least for the near future. This means that an exponential growth scenario for hydrogen production and the corresponding capacity would be more appropriate and, from such a perspective, the assumption that hydrogen production capacity follows a logistic growth function may not be justified. In the domain considered, one may thus choose for an exponential fit rather than for a logistic one. For completeness we therefore also include in Figs. 2(a)–(d) (with dashed lines) fits to our data set with an exponential growth function.

In order to determine learning curves for the investment costs needed to build hydrogen production facilities, we require cumulative installed production capacities. For each production method, we therefore have to determine the new production capacity constructed in every subsequent year. Figs. 2(a)–(d) show that the available production capacity for all production methods has increased over time. The increases observed in these figures, however, only account for part of the annual additions of production capacity. The reason is that new capacity also needs to be built for replacing plants that are closed down, because they have reached the end of their lifetime. To account for this replacement effect, we suppose that all production facilities are decommissioned after their typical designed lifetime of 30 years.⁷ For each year the total newly constructed hydrogen production capacity is the sum of the production capacity increase and the replacement for production capacity that has been phased out. The cumulative production capacity is the integral over time of the annually constructed new production capacity. The results of this exercise are depicted in Figs. 3(a)–(d) for each of the methods as well as their total. The uncertainty limits are determined by applying the same procedure described above to the uncertainty limits in Figs. 2(a)–(d). We will see that the spread reflecting this uncertainty in the cumulated production capacity affects the accuracy with which learning curves can be determined.

⁶ Sole exception is one data point in Fig. 2(b), because we considered this one unrealistically high.

⁷ Note that in practice old facilities are often retrofitted with state-of-the-art technology instead of entirely replaced like we assume here. We realize that our approach introduces a certain bias in our analysis, but we expect the effect to be small. The reason for retrofitting is usually to spare parts that are in good condition, and thus reduce capital requirements. Arguments remain, however, for nevertheless completely replacing aging facilities. One of which is that old plants are normally less efficient than new ones, which especially holds when fuel costs are large. We thus conclude that the potential error introduced by our assumption regarding replacements is limited.

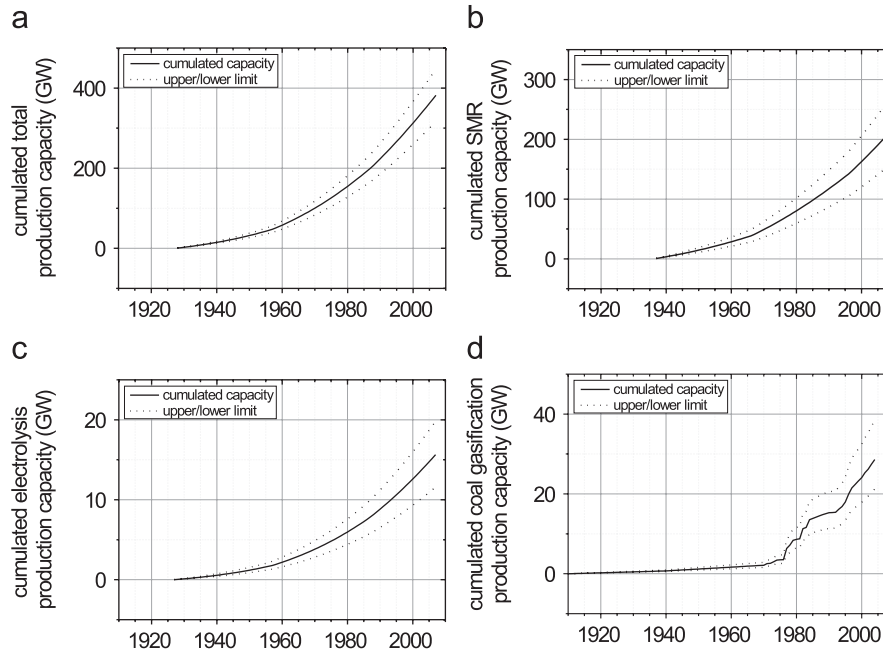


Fig. 3 – (a) Total cumulated global production capacity and cumulated global production capacities for (b) SMR, (c) electrolysis of water and (d) coal gasification.

The literature reports a figure of 26 MW production capacity in 1938. Since we take this year as the starting point of our integration, we neglect the capacity cumulated during the preceding years. The production capacity built between 1796 and 1938 thus in principle causes a systematic error in the total cumulative capacity we use in our learning curve analysis. We determined the size of this error by calculating the cumulative capacity for a straight line between the zero-production point in 1796 and the total production capacity of 26 MW in 1938. The offset created in the cumulated capacity amounts to 75 MW, which is negligible compared to the total cumulated hydrogen production capacity up to today, as shown in Fig. 3(a). This systematic error therefore does not have any significant effect on our learning curve calculations. The same holds for the individual methods of Figs. 3(b)–(d).

2.2. Cumulated amount of hydrogen produced

Analogously to the case of hydrogen production capacity, in order to construct a learning curve for the production costs of hydrogen, we first have to determine the cumulated amount of hydrogen produced as a function of time. In the literature sources we directly found the amounts of annually produced hydrogen for all cases except coal gasification. For the latter we needed to convert the coal gasification production capacity data into annual amounts of hydrogen produced, which we again performed by taking into account a 91% load factor. The solid squares in Figs. 4(a)–(d) show the global annual amounts of hydrogen produced for all methods combined as well as for each of the individual

categories. All amounts of hydrogen produced are expressed in TWh.⁸

The logistic growth fits in Figs. 4(a)–(d), their upper and lower limits, as well as the exponential growth fit, are all determined following the same procedure used for the annual production capacities of Figs. 2(a)–(d) in Section 2.1 for each of the four cases. The cumulated amount of hydrogen produced is calculated through simple integration, i.e. by determining the area under each of the curves of Figs. 4(a)–(d) depicting the amounts of hydrogen produced per annum. The result is shown in Figs. 5(a)–(d).

We again treated coal gasification slightly differently from the other three cases: the cumulated amounts of produced hydrogen in Figs. 5(a)–(c) were obtained by integration of the logistic growth curves of Figs. 4(a)–(c), while for coal gasification (Fig. 5(d)), the resolution of the data sets (for both the central values and the assumed outer limits) permits a determination of the cumulated level of hydrogen produced by simple addition of the annually produced amounts.

A systematic offset error in the cumulated amount of produced hydrogen, similar to the one found for the cumulated production capacity in the previous section, is caused by the amounts of hydrogen produced before 1938. The global hydrogen produced in 1938 was already 210 GWh [32]. The total cumulated global amount of hydrogen produced between 1796 and 1938 is estimated by integrating

⁸ One TWh corresponds to approximately 25 kt H₂, under the assumption that a TWh refers to the HHV energy content of hydrogen, that is, the HHV heat that would be released when hydrogen is combusted at 100% efficiency.

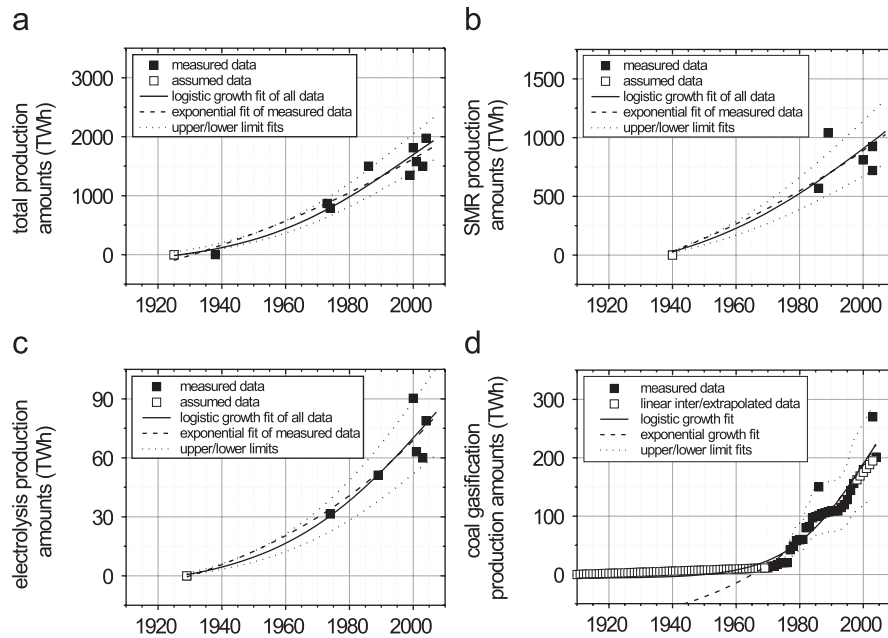


Fig. 4 – (a) Total annual global amount of hydrogen produced and the annual global amount of hydrogen produced with (b) SMR, (c) electrolysis of water and (d) coal gasification.

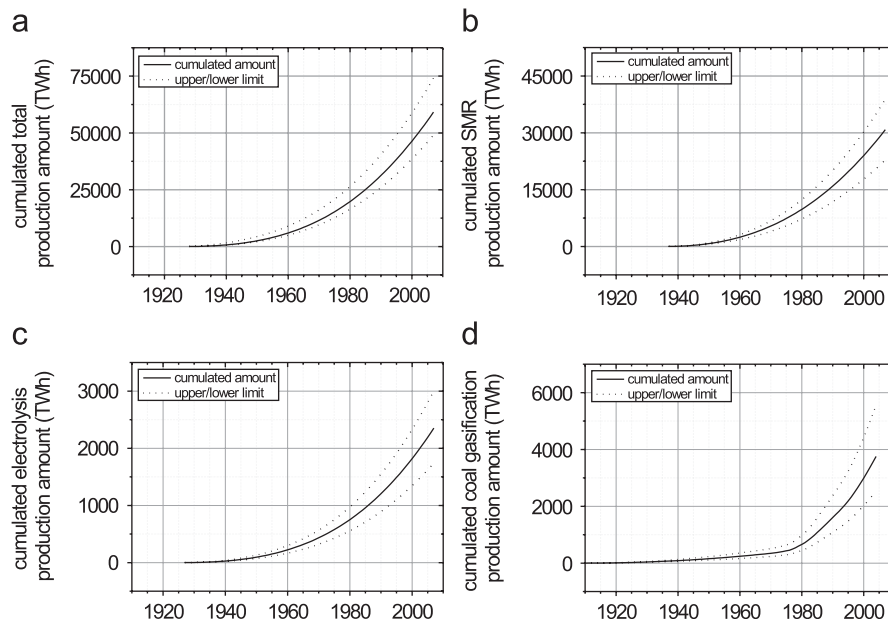


Fig. 5 – (a) Total cumulated global amount of hydrogen produced and the cumulated global amount of hydrogen produced with (b) SMR, (c) electrolysis of water and (d) coal gasification.

linearly between the zero-production in 1796 and the production amount of 210 GWh for 1938. The resulting systematic error in the total cumulated amount of hydrogen produced is at most 15 TWh, which we consider a negligible amount compared to the total cumulated amount of hydrogen produced up to today as shown in Fig. 5(a). The same holds for Figs. 5(b)–(d).

3. Costs of hydrogen production

Investment costs required for building hydrogen production capacity are extensively reported in literature, from which we developed a cost data set covering a time frame starting in 1942 for SMR and coal gasification, and in 1956 for electrolysis, and ending in 2007. We retrieved cost data for essentially two distinct activities: the building of hydrogen

Table 1 – SMR investment cost breakdown

Investment cost category	Share in investment costs ^a (%)
Inside battery limit costs	57 ± 20
Outside battery limit costs	17 ± 8
Contingencies	17 ± 8
Owners' costs	9 ± 4

^a Based on industrial-scale centralized SMR for the US gulf coast region [29].

production facilities (referred to as investment costs) and the production of hydrogen (production costs). By choosing the US\$ and 2000 as our reference currency and year, respectively, and correspondingly transforming all literature cost data and consequently reporting them in US\$(2000), we connect to the common convention in this field.⁹

3.1. Investment costs

Investment cost components for each of the three technologies SMR, electrolysis and coal gasification can essentially be categorized in four main contributions: inside battery limit costs, outside battery limit costs, contingencies and owners' costs [29]. Inside battery limit costs are the costs for building the hydrogen plant. Outside battery limit costs refer to site-specific costs such as those associated with connecting the plant to the surrounding infrastructure. Contingencies are costs related to unexpected events during construction, such as late delivery of parts, strikes or bad weather conditions. The costs associated with acquiring capital for financing the construction of the plant are referred to as the owners' costs. Owners' costs also typically include those related to administration and paper work. As for example, the investment cost breakdown for industrial-scale centralized SMR is shown in Table 1, with approximate uncertainty ranges for each of the cost component shares.

We express investment cost data consistently in kW.¹⁰ Fig. 6 shows the result of our investment cost data search, for the time frame from 1940 to today, for each of the three industrial-scale centralized hydrogen production methods. There is no consistent convention or agreement in the

⁹ It is well known that it matters what conversion rule is applied. We have chosen the US\$ as reference currency also for its long track record of exchange data from and to a large range of different other currencies. In our analysis, we first apply the currency conversion to US\$ at the point in time under consideration. Subsequently, we correct for inflation. We use three-year-averages of the exchange rate [34–36]. For the currency conversion we used additional information from [37,38]. In this paper we only consider industrial hydrogen production, and abstain from quantities produced in e.g. laboratories, because we consider the latter negligible. We use the “all commodities” producers price index (PPI), available from 1921 to 2006, to correct for inflation; since the PPI predominantly refers to industry, it serves as a suitable inflation index for our purposes [39].

¹⁰ We have chosen to use the HHV, so that 1 kW corresponds to the combustion of 7 mg of H₂ per second at 100% efficiency.

literature, and some authors even critically disagree, as to whether to include scaling effects in learning phenomena. We here choose to stick to the original meaning of learning-by-doing by excluding effects resulting from economies-of-scale. To compensate for these cost-size effects, all investment cost data are normalized to the investment costs for a hydrogen plant with a production capacity of 250 MW. We normalize the investment cost $C_{250\text{ MW}}$ by multiplying the investment cost from literature C_{lit} with the ratio between the production capacity S_{lit} reported in each literature source and the reference size $S_{250\text{ MW}}$ of 250 MW. This ratio is raised to the power $(1 - \lambda)$, in which λ is the scaling factor, in our case for either SMR ($\lambda = 0.70$), electrolysis ($\lambda = 0.90$) or coal gasification ($\lambda = 0.80$) (see [29]). The result is used to normalize the obtained literature cost data:

$$C_{250\text{ MW}} = C_{\text{lit}} \left(\frac{S_{\text{lit}}}{S_{250\text{ MW}}} \right)^{1-\lambda} \quad (3)$$

While we have no reason to doubt the veracity of the investment cost data found in the literature, we adopt uncertainty ranges over which these cost data may vary, in order to account for the error margins quoted in Table 1. The distinction between different cost categories and the spread in their share help us to identify the overall investment cost uncertainty. The total investment cost uncertainty values depicted as vertical error bars in Fig. 6 are calculated on the basis of the standard deviation of the outer limits of the investment cost shares of Table 1, to be uniformly 20% for all data points. The literature sources for the investment costs depicted in Fig. 6 are for SMR over the period 1942–2007 [18,20,23,25,27–30,40–48], for electrolysis over the period 1956–2002 [2,18,20,22–24,29,31,40,41,48–54] and for coal gasification over the period 1942–2004 [18,20,23,25,27–30,40,45,48,55,56].

Comparing Figs. 6(a)–(c) reveals that SMR requires the least investment costs per unit of production capacity. SMR is therefore today considered the leading hydrogen production technology. At present the investment costs for SMR typically lie between 200 and 400 US\$/kW, typically a factor two below those for coal gasification. Electrolysis accounts for the largest investment costs, which lie between some 500 and 1500 US\$/kW, while those for coal gasification lie between about 400 and 1100 US\$/kW. The 1942 data points should be considered with care, as they originate from war-time Germany, which makes it difficult to assess to what extent they may be related to post-war investment costs. We observe that the variation in the investment costs in Figs. 6(a)–(c) is large, for which at least four explanations exist. First is that over time several improvements in the production process became available for each of the three production methods. Note that it is not surprising that these three technologies could simultaneously co-exist, since the decision to choose for a given production process may not solely be driven by costs, but also, for example, by arguments of systems integration. Second, differences in e.g. steel prices may generate time-dependent variations in the total investment costs.¹¹

¹¹ A doubling in steel prices between 2004 and 2007 may partially explain the large increase in SMR investment costs observed over these years.

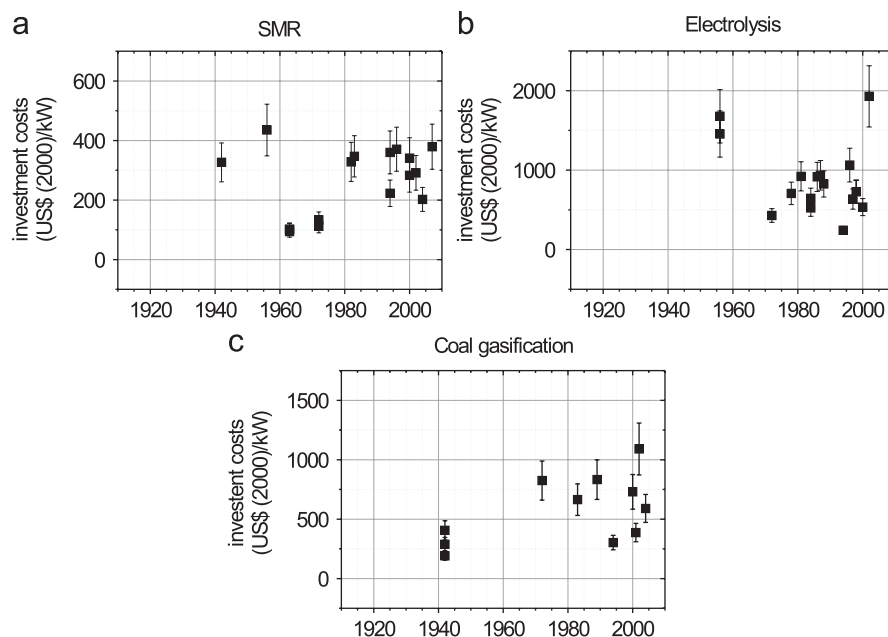


Fig. 6 – Investment costs for different hydrogen production methods as function of time: (a) SMR, (b) electrolysis and (c) coal gasification. The error margins represent a 20% uncertainty range uniformly assumed for all data.

Third, differences in quality requirements for the hydrogen end-use make the investment costs less comparable. Currently, half of the hydrogen is used for non-energy application in the chemical industry (mainly ammonia production), 20% is used for fuel refining in the petroleum industry and the rest (mainly lower quality hydrogen) is used for industrial process heat production. Depending on the quality requirements of the hydrogen needed for these processes, extra steps in the hydrogen production process are needed for e.g. purification. This leads to differences in the costs for building hydrogen plants (and for producing the hydrogen itself). Often the purpose of the hydrogen or the extra measures for meeting higher quality requirements are not mentioned in our literature sources, preventing us from accounting for these differences. On the other hand, the large uncertainty ranges we assume, partly account for the differences resulting from this effect. Fourth, investment cost variations may derive from the absence of a well-defined uniformly applied definition of investment costs, so that each individual data point might actually be based on a (somewhat) different subset of cost categories. Of the 35 literature sources examined, only five reports give appropriate insight into the detailed investment cost breakdown.

3.2. Production costs

Total hydrogen production costs for industrial-scale centralized SMR and electrolysis can be categorized in three main components: capital charges, fuel and electricity costs and operation and maintenance costs (see Table 2). The capital charge component includes all investment costs, levelized over the lifetime of the plant to allow an expression in terms of US\$/kWh. The fuel and electricity cost component primarily accounts for the main input required for the

Table 2 – Cost break-down for hydrogen production via SMR and electrolysis in 2002 [29]

Production cost category	Share in production costs	
	SMR (%)	Electrolysis (%)
Capital charges	29	40
Fuel and electricity	61	47
Operation and maintenance	10	13

Since gas prices fluctuate significantly, the share of the fuel and electricity cost component is subject to substantial change.

hydrogen production process—natural gas for SMR and electricity for electrolysis—but also includes a variety of additional costs associated with e.g. the fuel needed to run the plant, as well as the use of offices, vehicles and other auxiliary services. Operation and maintenance costs cover notably the labor costs associated with running the plant and keeping it in optimal and safe conditions.

Since gas prices are characterized by large fluctuations, over time and by region, the share of the fuel and electricity cost component in the SMR column of Table 2 may be subject to considerable change. Naturally, this affects all relative contributions to the total hydrogen production costs for SMR. More limited but otherwise similar cost share variations may be observed for electrolysis (see the last column of Table 2). To point out the extent by which the fuel and electricity cost share for SMR may vary over time, Fig. 7 depicts the evolution over much of the 20th century of the natural gas wellhead price index conjointly with the development of the PPI over this time frame. Whereas there is a certain correspondence between the two depicted curves,

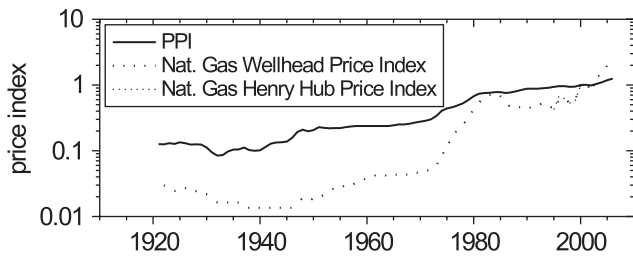


Fig. 7 – Evolution of the PPI, the US natural gas wellhead price index and the so-called natural gas Henry Hub Price index (only between 1995 and 2000) [39,57]. The natural gas wellhead price index and the natural gas Henry Hub price index are based on money of the day (in current terms). All data are normalized with respect to their value of the year 2000.

both more or less synchronously displaying increasing tendencies, the large superimposed fluctuations of the natural gas price, relative to the PPI, result in a strong time-dependence of the share of the fuel and electricity cost component. A rule of thumb for the different cost contributions for SMR is that the lion's share of the total costs is determined by fuel (natural gas) charges and that the remainder is distributed over capital charges versus operation and maintenance costs in a ratio of 3:1. For the listed electrolysis cost share distribution the revenue generated by the selling of oxygen delivered as byproduct, typically amounting to about 2% of the overall hydrogen production costs, is not taken into account.

Total hydrogen production costs are shown in Figs. 8(a)–(c) for each of the three production methods, all expressed in US\$(2000)/kWh.¹² Similar to the investment costs discussed in Section 3.1, there is no reason to doubt about the truthfulness of the production cost data gathered from the open literature and assembled in Fig. 8. Still, also here we consider it appropriate to adopt uncertainty ranges over which these cost estimates may vary. To reflect the presence of sizeable variations in total production costs, especially as a result of price volatilities of inputs like natural gas, we assume relative error margins of 30% with respect to the reported central values, and represent these as vertical error bars in Fig. 8. The value of 30% is inferred from the cost shares listed in Table 2 and the natural gas price fluctuations depicted in Fig. 7.

The strong deviation of total SMR hydrogen production costs in 1983 (Fig. 8(a)) results from the high value of the variable (fuel) costs assumed in the corresponding literature source [16]. The large increase of the spread in total electrolysis production costs over time (Fig. 8(b)) can be explained by the different electricity generation alternatives employed for this method's main input. In some cases only relatively costly power remains accessible, while in others cheap electricity has progressively become available for supply to electrolysis plants. Indeed, the electricity used for electrolysis may originate from options as diverse as

relatively cheap (hyper-competitive) off-peak hydropower to fairly expensive (sub-competitive) wind power. The literature sources used for collecting the hydrogen production cost data depicted in Fig. 8 are for SMR over the period 1960–2003 [2,16,17,23,27–30,48,58–63], for electrolysis over the period 1972–2004 [2,22,23,28,48,50,52] and for coal gasification over the period 1942–2002 [2,23,27,55,63,64].

As we can see in Fig. 8, total hydrogen production costs via SMR and coal gasification are rather similar, generally lying in both cases around 0.02–0.03 US\$/kWh. In the previous section it was pointed out that roughly a factor of two difference exists between the investment costs for SMR and coal gasification. It thus proves that the difference in fuel costs between these two options, significantly lower for coal gasification than for SMR, more or less compensates for the discrepancy in investment costs. Hydrogen production through electrolysis is always significantly more expensive than by these two fossil-based options, sometimes even by an order of magnitude. Even if we only consider electrolyzers that are fed with the cheapest (or free) off-peak electricity, such as produced by nuclear and hydro power plants during off-peak periods when these constitute surplus capacity, electrolysis is still the most expensive production method at around 0.03–0.25 US\$/kWh. The variations in production costs depicted in Fig. 8 may be caused by the co-existence of different types of processes within each of the three production methods and differences in quality requirements of the end-users. Different interpretations of the underlying cost breakdown may also lead to a certain variability. Still, since the combined variable costs account for as much as 60–70% of the total production costs, we think that the time-variability (and unpredictability) of this cost component has the most sizable effect on the total production cost volatility. Furthermore, costs and notably variable costs may have some geographic dependence, since certain prices like of fuel, electricity and labor can partly be determined by local markets and conditions. Regional differences constitute the likely origin of the spread in coal gasification cost data of Fig. 8(c), which may be affected by e.g. the distance over which imported coal must be transported.

4. Learning curves

4.1. Hydrogen production capacity

We are now in a position to combine the cumulated capacity data reported in Section 2.1 with the investment cost data of Section 3.1. Hereby we obtain the double-logarithmic plots of Fig. 9, thus showing the dependence of the investment costs on the cumulated experience acquired in building (a) SMR, (b) electrolysis and (c) coal gasification hydrogen production plants. The horizontal and vertical error bars depicted in Fig. 9 are the uncertainty ranges as derived in the corresponding Figs. 3 and 6, respectively.

At first sight, there appears to be a large variation in the data points in Figs. 9(a)–(c). A closer examination of the employed literature sources reveals that in a few publications not all four investment cost categories as mentioned in Table 1 were explicitly taken into account. The open squares

¹² We use again the HHV, so that the combustion of 25 g H₂ at 100% efficiency corresponds to 1 kWh.

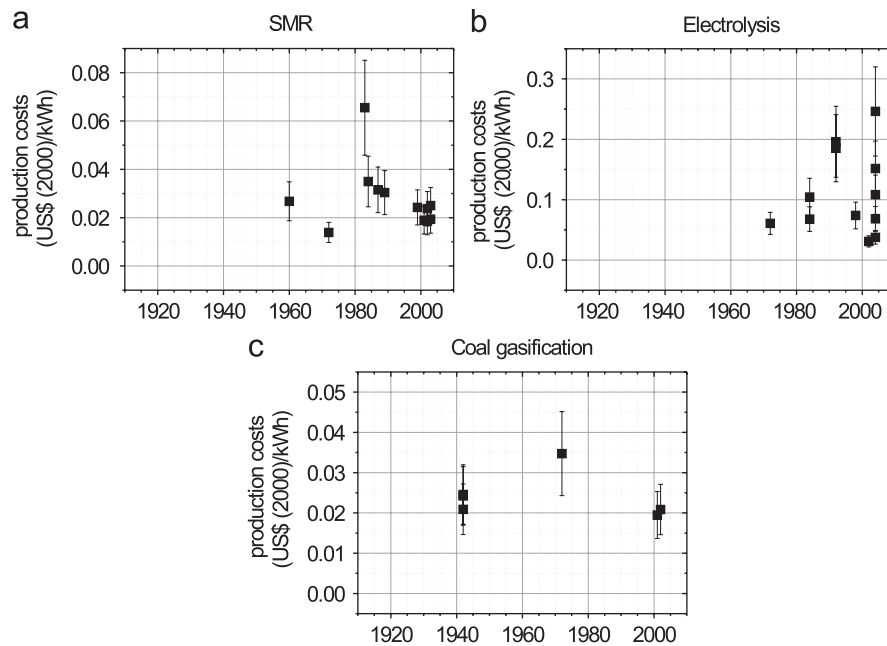


Fig. 8 – Total costs for different hydrogen production methods as function of time: (a) SMR, (b) electrolysis and (c) coal gasification. The error margins represent a 30% uncertainty in the overall production cost estimates.

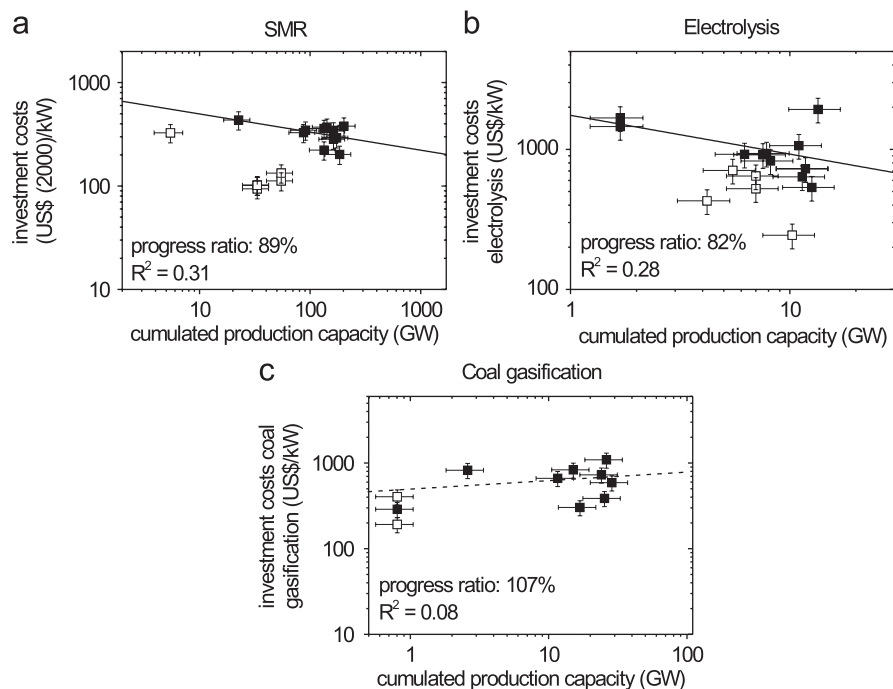


Fig. 9 – Learning curves for the investment costs of different hydrogen production methods: (a) SMR, (b) electrolysis and (c) coal gasification. The solid lines represent low but statistically still meaningful learning curves, while the dashed line represents an unreliable fit.

in Fig. 9 are investment cost data for which we found strong evidence that they are incomplete, that is, that at least one of the investment cost components must have been left out.¹³

¹³ The meaning of open and solid squares here is not to be confused with that in Figs. 2 and 4.

In most of our literature sources, the precise breakdown of the reported investment costs is not described, both for data where we could nevertheless infer that all cost categories were included and for those for which we suspected that this was not the case. Hence, we could usually not estimate by how much precisely the incomplete investment

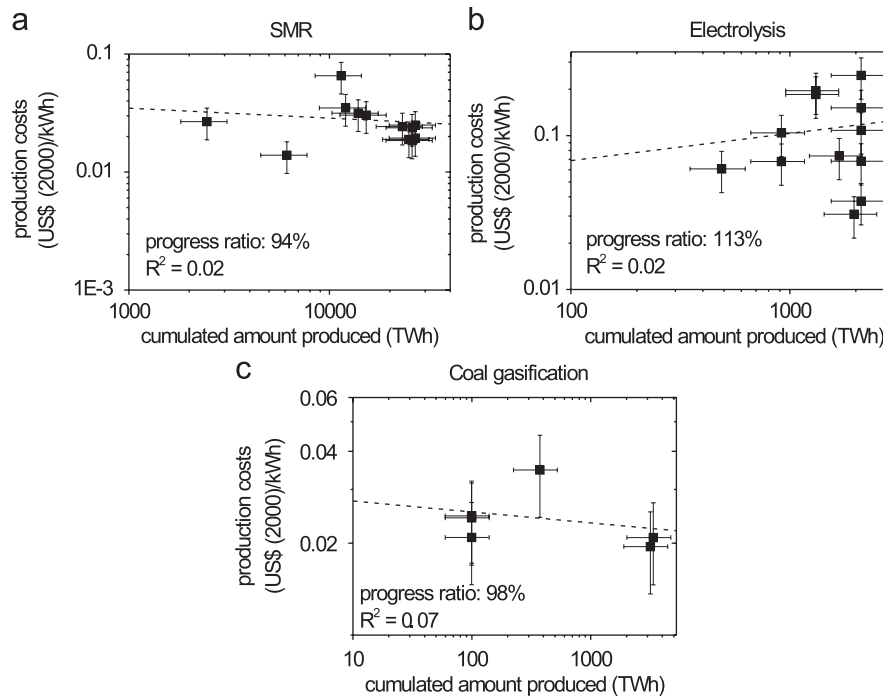


Fig. 10 – Learning curves for the production costs of different hydrogen production methods: (a) SMR, (b) electrolysis and (c) coal gasification. The dashed lines represent unreliable learning curves.

costs were off from the complete ones. Also, incompleteness could originate from the omission of different cost components, so that the composition of each data point could be different. Consequently, we discarded the open square points from the set to which we apply the fitting procedure that allows us to determine the learning curve. We performed fits only to those investment cost data for which we could confirm that all cost categories were taken into account.

Each line through the data points in Figs. 9(a)–(c) is the result of a least square power-law fitting procedure. This allows us to determine the learning curve defined in Eq. (1) and, on the basis of the slope of this curve (the learning index), to calculate the progress ratio with Eq. (2). Based on the ensuing correlation coefficient R^2 we were able to find two statistically meaningful learning curves, for SMR and electrolysis, drawn as solid lines in Figs. 9(a) and (b), respectively. In each of these two cases, the correlation is rather low, with a coefficient of approximately $R^2 = 0.3$, but of all instances considered this outcome was the best we were able to obtain. The learning curve for coal gasification in Fig. 9(c) has been rejected, because it shows no correlation with a power-law ($R^2 = 0.08$), and is therefore shown by a dashed line.

The learning curve in Fig. 9(a) shows that the investment costs for SMR hydrogen production capacity proves to learn with a $pr = 89 \pm 6\%$ ($lr = 11 \pm 6\%$). While the learning-by-doing literature rarely reports error margins on calculated progress ratios or learning rates, given the sizeable spread that exists in the investment costs we judge it necessary to determine an error margin for these parameters. The fact that

we have made particular effort to validate uncertainty ranges for our data points, in both relevant dimensions, allows us to determine these error margins. For SMR these were determined by the Gauss error propagation law. For the required initial SMR cost and its error margin we used a value of $c_0 = 745 \pm 274$ US\$/kW.¹⁴ For the investment costs for electrolysis, the learning-by-doing proves to be more significant, with a value of $pr = 82 \pm 13\%$ ($lr = 18 \pm 13\%$). The error margin for the electrolysis progress ratio (larger here than for SMR) was determined using the same procedure as for SMR, on the basis of the corresponding initial cost of electrolysis amounting to $c_0 = 1750 \pm 406$ US\$/kW.¹⁵ The results we find for the investment costs needed for the construction of SMR and electrolysis hydrogen production plants indicate that only limited learning takes place in each of these two cases. For both SMR and electrolysis the progress ratio and corresponding uncertainty range lie well within the range of progress ratios reported for energy technologies at large in the literature [65]. Since the investment cost data for the construction of coal gasification hydrogen plants do not follow a power-law, we conclude that one cannot discern any learning for this production method.

¹⁴ Alternatively, the error margin can be determined by drawing learning curves between the upper initial cost margin and the highest error margin of all other data points, respectively, the lower initial cost margin and the lowest error margin of all other data points. We then find error margins for pr of 1% and 2%, respectively.

¹⁵ The alternative determination of the error margin explained in the previous footnote results in a value of 9% in each of the two cases.

4.2. Producing hydrogen

Figs. 10(a)–(c) show the double-logarithmic plots for the costs associated with the production of the equivalent of 1 kWh of hydrogen (Fig. 8) versus the cumulated amount of hydrogen produced (Fig. 5), for (a) SMR, (b) electrolysis and (c) coal gasification, respectively. The horizontal and vertical error bars correspond to the uncertainty ranges as derived in these corresponding respective sections. Each line through the data points in Figs. 10(a)–(c) is again the result of a least square fitting procedure on the basis of the power-law of Eq. (1). For each of the three depicted production methods, the cost data do not clearly fit to this power-law, confirmed by the low values of the correlation coefficient R^2 . This leads us to conclude that no learning-by-doing behavior can be observed for overall hydrogen production activity, for any of the three production methods.

The likely explanation for the fact that we do not observe learning for producing hydrogen are the large variations of data points in Fig. 10, reflecting that overall production costs also contain variable costs like operation and maintenance, and fuel and electricity costs. For all three production techniques, total costs are determined for 60–70% by variable costs and thus highly sensitive to variations that either have a non-learning nature or from which no learning can be distinguished through the noise of variability. As we saw in Fig. 7 for the case of SMR, the share of the fuel and electricity costs in total production costs changes when natural gas prices do not follow the PPI. Because this share of fuel costs is large, even a relatively modest change in fuel prices may cause fluctuations in the overall production costs that dwarf learning-related cost reductions (if available at all, of course). We find that the sensitivity of hydrogen production costs to volatile or non-learning cost components renders this technology in principle unsuitable for the determination of learning curves. This problem might be partially circumvented by isolating the fuel prices from the production costs and thus attempting to determine a learning curve for one of the components (in e.g. one particular region) only. We suspect that it may remain difficult to account for uncertainties related to fluctuations in market prices of other relevant input goods.

5. Discussion

At least as meaningful as these two statistically significant learning rates, is our result that we were not able to find learning-by-doing at all for the costs associated with any of the complete hydrogen production processes. For hydrogen production costs as function of the cumulated amount of hydrogen produced, as shown in Fig. 10, we observe no power-law correlation, in none of the three individual cases we analyzed. Since the 1940s hydrogen is produced as a bulk product. Therefore, one may expect buyers on the market to go for the cheapest hydrogen (locally) available and thus one may expect cost reductions to be a strong driver for large-scale hydrogen production. Still, there may be several reasons for why the learning curve methodology seems not applicable to our hydrogen production cost data, or alternatively, if costs

are subject to learning, why no learning can be observed for this process.

First, production costs include, in addition to investment costs, variable costs like operation and maintenance costs, fuel and electricity costs, as well as labor costs. Variable costs depend on market prices which may fluctuate in time and differ from region to region. We know that this is especially true for fuel and electricity costs: the price variability of methane for SMR is a good example. These variable costs do not learn, and even if they do—operation, maintenance and labor costs are often subject to learning-by-using—cost reductions may still be obscured by their intrinsic volatility. As variable costs account for as much as 60–70% of total production costs, as is the case for SMR and electrolysis, large fluctuations of the variable costs shadow the parts of the production costs that typically do learn, such as investment costs. Second, the values for the production costs were extracted from several different studies in the literature. Discrepancies exist in the way total production costs are reported in different sources. It is not always possible to determine what exact cost contributions are accounted for, and it is even unlikely that all studies always use the same definition for what elements are precisely included in overall production costs. This may be another source of cost data variability that can dwarf the modest learning available for some of the cost components (as we demonstrate for construction investment costs). Finally, since natural gas prices went up, the necessity for building more efficient SMR plants increased. This led to higher capital expenditures, shadowing the apparent learning.

Investment costs are less blurred by large variations over time, because they are less sensitive to cost components that heavily fluctuate like those determined by market prices of such essential inputs as fuels and electricity. We found little concrete indications that substantial differences occurred from labor costs diverging from one region to another. Of course, investment costs also show a certain level of variability, since they are sensitive to e.g. material prices like those of steel. We expect that over the past few decades this type of cost variability has been smaller than the corresponding one for a fuel like natural gas. Also, for the referenced investments costs we found quite clear evidences that they were often not determined following the same definition. In quite a few publications, for example, clearly not all four cost categories as mentioned in Table 1 were explicitly taken into account. It proved often impossible, however, to determine which cost components were missing, because in most cases the precise investment cost break-down was not known. Hence, we could usually not estimate by how much precisely the incomplete investment costs were off from the complete ones. But the fact that some cost components were evidently missing allowed us to discard them from the data set on the basis of which to determine our learning curves. We hereby eliminated much of the observed cost variability, and hence could extract a learning 'signal' from the cost 'background noise'. In Fig. 9 we depicted with open squares the incomplete investment cost data that were, for these reasons, excluded from the final learning curve analysis.

A specific intricacy one encounters while attempting to apply the learning curve methodology to hydrogen production

is that one should be attentive to the fact that the costs reported by different authors may often display significant discrepancy in the way the level of financing costs are estimated. Differences and the assumed levels of contingencies, owners' costs and capital charges result in variations in both the investment costs of Fig. 9 and the production costs of Fig. 10. This problem arises regardless of whether all cost categories are taken into account and generates an additional spread in the data, which inhibits our ability to determine the presence of learning phenomena.

The two statistically meaningful learning curves we derived for the investments needed for the construction of SMR and electrolysis facilities only show limited learning. This does not mean, however, that the building of these hydrogen production technologies has only modestly changed over time. In fact, there is substantial evidence that the opposite is true. Since the 1940s much and continuous technological progress has been made for both SMR [23,44,66,67] and electrolysis [21–23,25]. We end this section by speculating what the reasons could be for the fact that so little learning can be observed for hydrogen production construction costs, and why we see no cost reductions at all for hydrogen production process costs. If observed costs have basically not gone down, why and how did the effects of technological improvements on these costs get cancelled?

Increasing energy prices have been a drive for designing and building plants that are more efficient and make better use of the main input resources, such as natural gas in the case of SMR. Technologically advanced efficient plants are more expensive than older types of less efficient plants. This could be a first explanation why cost reductions in some parts were shadowed, and why overall investment costs have not gone down. A second reason is that health, safety and especially environmental requirements have become much more stringent over time, which has led to significantly more expensive plant designs. A parallel can here be drawn with the case of nuclear power. In the case of nuclear energy, the investment cost reductions expected for nuclear power plants in the 1960s never materialized. Instead, investment costs increased over the past decades, mainly as a result of increasingly stringent requirements regarding notably plant operation safety. The costs associated with these additional safety measures have generally dwarfed the cost reductions achieved for other nuclear power cost components. A third explanation may be that today the produced hydrogen is subject to stricter quality specifications than in the early days of hydrogen production. This means that operators of e.g. SMR plants have to invest more in gas cleaning equipment in order to meet current hydrogen quality standards. These additions may obscure possible cost reductions in other aspects of the production process. Finally, the different quality requirements for different hydrogen end-use applications make the investment and production costs less comparable. The three former types of arguments presumably hold similarly for many large-scale industrial plants, production methods and energy technologies, so that it may be difficult to observe learning curves for these cases more generally than the specific hydrogen-related one analyzed in this paper. Indeed, there is for example little mention of learning-by-doing in the open literature on activities in the nuclear industry.

The cost development of hydrogen production is only part of the total costs of hydrogen use in for example automotive applications. It is the costs of hydrogen delivered to the tank plus the costs of its end-use in e.g. fuel cells that really counts. The costs for hydrogen delivery to the tank comprise of hydrogen production, distribution and storage. Future research has to show how the costs of the latter two shackles in the chain develop.

6. Conclusion

In this article we have attempted to develop learning curves for two essential components of a 'hydrogen economy': the construction of hydrogen production facilities and the production process of hydrogen with these facilities. Three hydrogen production methods were examined: SMR, coal gasification and electrolysis of water. We managed to include data in our analysis that go far back in time, which, in principle, greatly benefited the statistical significance of our analysis. Especially the older data, however, are characterized by a variety of uncertainties, which rendered the development of reliable learning curves challenging. Still, several of our findings prove to shed light on the future economic viability of the widespread use of hydrogen, and we believe we can draw a couple of robust conclusions.

We find only limited learning at best in a couple of cases, and no cost reductions can be detected for the overall hydrogen production process. Of the six hydrogen-related activities investigated, statistically meaningful learning curves can be determined for just the investment costs required for the construction of SMR facilities, with a learning rate of $11 \pm 6\%$, and electrolysis equipment, with a learning rate of $18 \pm 13\%$. For coal gasification facility construction costs no learning rate can be discerned. The learning rates calculated for SMR and electrolysis equipment construction costs have large error margins, but the central values and their uncertainty ranges lay well in the range of the learning ratios reported in the literature for other technologies in the energy sector.

The absence of a reduction of costs associated with the complete hydrogen production process together with the limited cost reductions we observed for investments in hydrogen production facilities leads us to question whether the expectations around learning effects in general, and especially for large-scale technologies, are really justified. The main basis for the optimism around learning curves is that they have been observed for many technologies. It has been observed, however, that the sample of technologies that learn may be strongly biased, since learning can by definition only be determined for technologies that have survived the test of time, and learning rates are usually only reported for technologies to which the learning curve methodology has been successfully applied [14]. The downside of this one-sided reporting is that it might invite one into unbalanced view on the applicability of learning curves to estimate future cost reductions, as if cost improvements take place in general for all energy technologies under all circumstances. Here we have shown that at least for the case of hydrogen production this optimistic view is probably incorrect. On the other hand,

we expect that the overall costs of the use of hydrogen are more critically determined by the costs of fuel cells. Also, on the basis of the arguments made above, an interesting question can be raised to whether the present high expectations of cost reductions for similar large-scale technologies like CCS are justified.

The current production costs of hydrogen we find for SMR are in a range of 0.02–0.03 US\$/kWh, precisely central around the US Department of Energy cost target of 0.025 US\$/kWh for hydrogen production by SMR [3].¹⁶ So, in principle, the price target has already been reached. Our cost estimate, however, is based on gas prices prior to 2003 which are low compared to today's values. Also in the future we expect price rises related to e.g. problems with the long-term security of supply of natural gas. Hence, unless these effects lead hydrogen production to become significantly more expensive than the current range, there is in principle no problem that SMR does not learn (at least according to the US Department of Energy with its cost target for hydrogen production by SMR).

Our results indicate a cost range of 0.03–0.25 US\$/kWh for hydrogen production through electrolysis, which in most cases is much higher than the US Department of Energy target of 0.05 US\$/kWh [3]. This large cost range results mainly from the variety of sources the electricity input is generated from. The investment costs we find for electrolysis are currently around 1000 US\$/kW. Given that we use open literature sources, we should probably consider this as a minimum lower bound. Using annual capital charges of 18% of the investment costs and an overall process efficiency of 68% [29], we calculate that the lowest possible investment charge per kWh of hydrogen production through electrolysis is about 0.03 US\$. This means that electrolysis will meet the US Department of Energy target when electricity does not cost more than 0.02 US\$/kWh. However, electricity costs of 0.10 US\$/kWh seem to be more realistic. Hence, to meet the cost target set for electrolysis, both the investment costs and the electricity costs have to come down. The type of electrolysis equipment we investigate in this paper is essentially the alkaline electrolyser. Our results indicate that cost reductions are not likely to be realized for this type of electrolyser. Therefore we might (need to) see a gradual switch from alkaline to PEM electrolysers, as the costs of the latter may be more readily scaled down to the desired levels.

Acknowledgments

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¹⁶ The background behind why the US Department of Energy has precisely these targets is subject of future analysis.

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