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[EWI-Study]

The Power of Scale

Economies of Scale and the Hydrogen Value Chain

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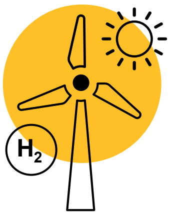

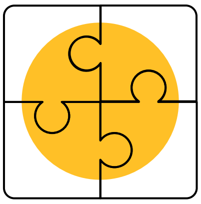

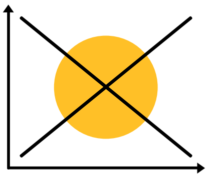

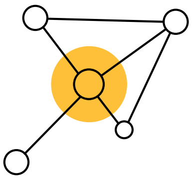

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Executive Summary

The hydrogen market ramp-up is an important factor for reaching near-term and long-term climate goals in Germany and Europe. For low-carbon hydrogen to be competitive, the cost of hydrogen must decrease, the cost of fossil energy carries must increase, or both. This study deals with the cost reduction of hydrogen through economies of scale.

In many studies, the expectation of cost degressions is justified with upcoming "Economies of Scale" (EoS), without further clarifying this term or specifying the source of the cost reductions. Therefore, we first analyze and define the term EoS from an economic point of view and discuss the main drivers. Then we transfer the general findings from the economic theory on EoS to the hydrogen value chain. The graphical abstract shown in Figure 1 gives an overview of the study, including a definition of internal and external EoS.

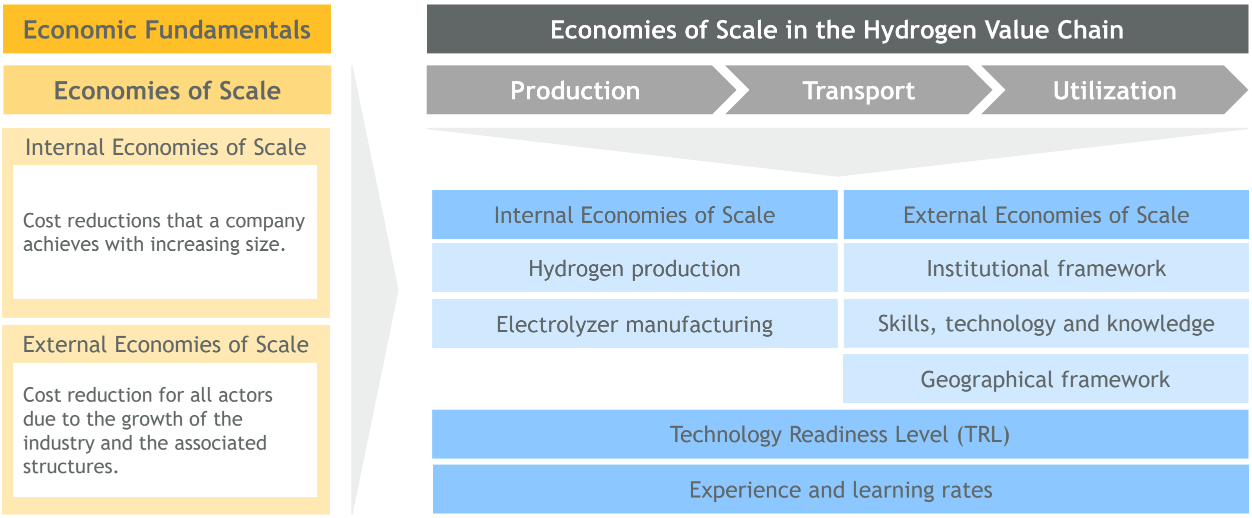

Figure 1: Graphical abstract

Source: Own illustration

General Concept of Internal and External Economies of Scale

Internal EoS describes the structures within a company that leads to the reduction of per-unit costs due to increased production volumes. Larger companies tend to have opportunities to reduce per-unit costs, for example, through better access to financial markets, bulk purchasing, or the ability to exploit physical EoS.

In contrast, **external EoS** occur if the corresponding industry grows. External EoS may follow through an institutional or geographical framework and skills, technology, and knowledge creation. Important factors leading to internal and external EoS are illustrated in Figure 2.

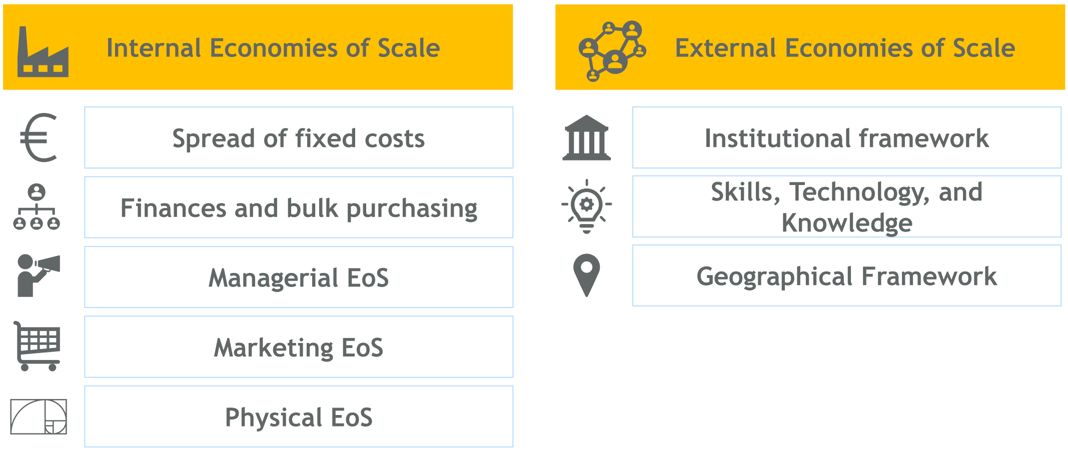

Figure 2: Drivers of positive internal and external Economies of Scale

Source: Own illustration

Internal Economies of Scale in the Hydrogen Value Chain

Especially in hydrogen production and hydrogen transport, internal EoS can be expected. When producing **hydrogen from fossil fuels** via steam methane reforming or coal gasification, a scale-up from a small to a large plant can significantly reduce costs. The production costs of coal gasification are generally higher than those of steam methane reforming. But, coal gasification exhibits stronger internal EoS than steam methane reforming. To mitigate greenhouse gas emissions in fossil hydrogen production, carbon capture, and storage (CCS) can be employed. The cost structure of CCS is capital intensive, so its application is favorable for high utilization rates, i.e., large-scale industrial application.

EoS are relevant to **electrolytic hydrogen production** in two ways. Firstly, increasing electrolyzer manufacturing capacity of a factory can significantly reduce the manufacturing costs of an electrolyzer stack. Secondly, increasing electrolyzer system capacities reduces the costs of an electrolysis system as the balance of plant components like gas processing equipment underly EoS. However, the electrolysis stack itself is modular and therefore does not underly EoS. As the stack accounts for approximately half of the total system costs, increasing the plant capacity leads to less significant EoS in electrolytic hydrogen production than in conventional hydrogen production.

The preferable mode of **transportation of hydrogen** depends mostly on the quantity. Trailers are the most economical option for small quantities, suitable for last-mile distribution or low-demand areas. Pipeline transport is considered the most cost-effective option for long distances and regular hydrogen transportation. Transportation via pipelines exhibits high EoS; for example, due to physical EoS, the unit investment costs decrease by 50 % if the pipeline radius doubles. Furthermore, investment costs of pipelines are high and operational costs low, such that higher utilization rates decrease costs per transported unit of energy.

External Economies of Scale in the Hydrogen Value Chain

In contrast to internal EoS, external EoS can be expected throughout the hydrogen value chain. Factors leading to external EoS can either stem from the institutional framework, skills, technology and knowledge, or the geographical framework.

A stable and supportive **institutional framework** for hydrogen, including dedicated laws, regulations, technical standards and codes, Guarantees of Origin (GoO), internationally harmonized standards, and a green hydrogen certification scheme, can support innovation and investment, facilitating EoS. Institutions and organizations can offer a platform for knowledge and experience exchange. The increasing number of hydrogen-related institutions and associations indicates that the hydrogen market ramp-up is progressing. Thus, the potential to achieve external EoS through supportive institutions is increasing. In addition, policy instruments, e.g., capital expenditures (CAPEX) and operational expenditures (OPEX) subsidies, mandatory quotas, Carbon Contracts for Difference (CCfD), or Contracts for Difference (CfD), can support EoS and cost reductions in the hydrogen value chain.

Skills, technology, and knowledge support external EoS in the hydrogen value chain through various channels, such as R&D activities, skilled labor, education, training programs, and formal and informal knowledge spillover. Especially private and public research and development (R&D) activities and spendings are crucial to lowering the costs of hydrogen technologies. The availability of skilled labor facilitates EoS. Skilled labor could, however, form a bottleneck as specific knowledge and expertise on hydrogen is needed for the hydrogen market ramp-up. Specific education programs for the skills demanded by the industry lead to positive external EoS. The private and public sectors offer various programs focusing on hydrogen. With the proceeding hydrogen market ramp-up, the number of programs is increasing. Growing expertise and knowledge are expected to enable formal and informal knowledge spillovers in the hydrogen economy.

The **geographical framework**, especially physical proximity, can play a significant role in achieving EoS. EoS can be promoted using existing or the construction of new infrastructures, the location of specialized suppliers, or a pool of skilled workers. These conditions can be present, e.g., in hydrogen clusters. Hydrogen clusters accelerate EoS and positive network effects. Clusters of grey hydrogen exist already today. Thereby, hydrogen consumers are connected via pipelines to minimize hydrogen transport costs. If existing skills and capabilities, e.g., from grey hydrogen usage or handling natural gas, can be applied to developing hydrogen-specific skills, this may result in a regional advantage through the potential of EoS. As clustering hydrogen production and utilization offers various advantages, some policies specifically support the formation of hydrogen clusters.

Chances for EoS in the early stage of the hydrogen market ramp-up

Public actors especially have major potential to facilitate EoS and cost reduction in the hydrogen value chain. For example, economic benefits from subsidies or tax advantages can enable the exploitation of internal EoS. In the early stage of the hydrogen market ramp-up, the legal and regulatory framework can influence various factors that support external EoS along the hydrogen value chain. Governments and public authorities can facilitate external EoS by supporting the institutional framework, skills, technology and knowledge, and the geographical framework.

1 Motivation

Achieving climate neutrality requires the phase-out of fossil fuels since the combustion of fossil fuels is responsible for a large share of greenhouse gas (GHG) emissions. The demand for fossil fuels can be reduced by energy-saving measures and increasing energy efficiency, for instance, via direct electrification of processes and end-use applications. On the supply side, energy carriers like green or low-carbon hydrogen can replace fossil fuels. Currently, hydrogen is primarily used as a feedstock in the industry. In 2021, approximately 48 TWh of grey hydrogen was consumed in Germany (EWI, 2023).

The demand for green hydrogen and hydrogen-based products is expected to increase to reach climate neutrality (see Figure 3). A meta-analysis of the German gas and hydrogen demands in 27 normative energy system scenarios shows that the average hydrogen demand reaches 300 TWh per year for scenarios with climate neutrality. This potential hydrogen demand represents a six-fold increase compared to the German hydrogen demand in 2021 (see Figure 3).

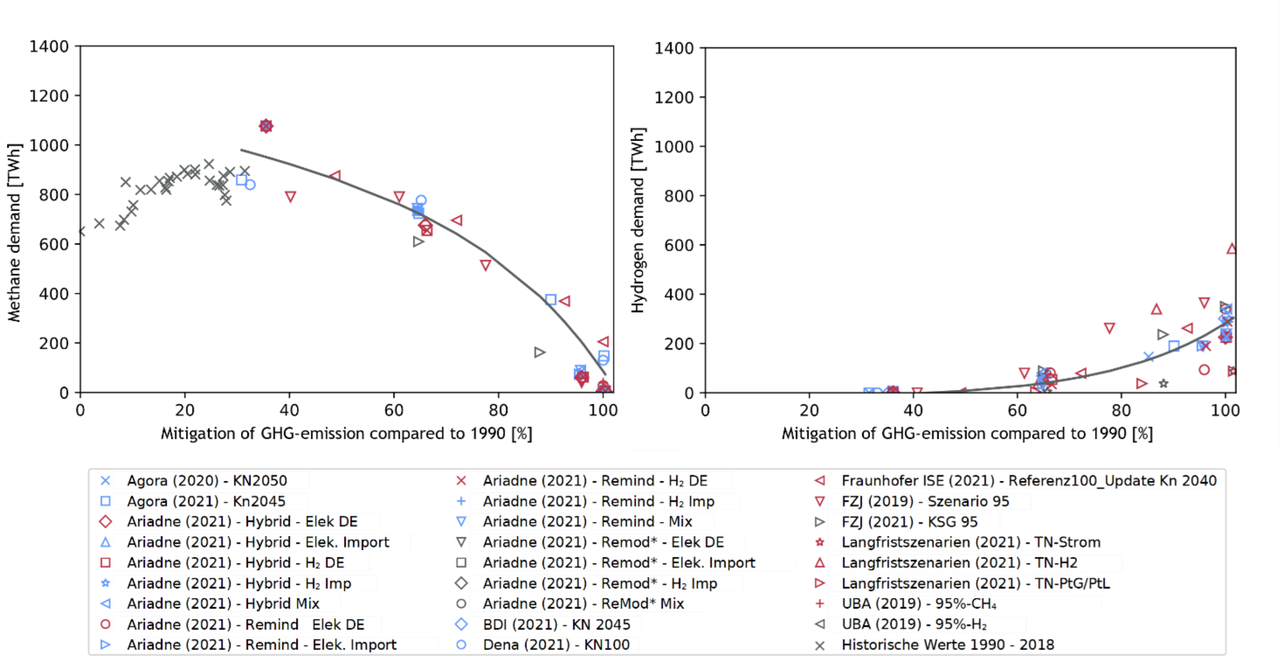

Figure 3: Methane and hydrogen demand from several normative energy system scenarios in Germany in dependency of the GHG mitigation compared to 1990.

Source: (Kopp et al., 2022)

According to the coalition agreement of the German government, an electrolysis capacity of 10 GW has to be installed by 2030 to meet the demand for green hydrogen (SPD et al., 2021). Following the recently published “H_2 Bilanz”, a total installed capacity of 8.1 GW_{el} of electrolysis projects will be installed by the end of 2030 if every publicly announced project is realized (EWI, 2023). It should be emphasized that a final investment decision has scarcely been made for any projects, and the probability of realization cannot be estimated. The electrolysis capacity installed in Germany must significantly expand in the upcoming years to achieve political targets. Moreover, sufficient infrastructure must be created to connect production and consumption. The rapid establishment of a hydrogen economy, the ramp-up of hydrogen supply and demand, and the development of hydrogen infrastructure face numerous challenges that must be overcome.

Green and low-carbon hydrogen is not competitive with its fossil and carbon-intensive alternatives today. Considering the future, however, various reports expect the production, distribution, and application of hydrogen to witness substantial cost reductions. More precisely, they point to the significant potential of economies of scale (EoS). Since EoS may not only apply to the manufacturing process but also when it comes to the technical improvement of hydrogen technologies, technical learning rates, and automatization, they are expected to reduce the costs of hydrogen production substantially (dena, 2019; Hydrogen Council, 2020; Prognos, 2020; Prognos et al., 2021). The International Energy Agency (IEA) assumes in its Net Zero Emissions by 2050 Scenario (NZE) a 60 % cost reduction for capital expenditures (CAPEX) of water electrolysis thanks to learning effects and EoS by 2030 compared to 2020 (IEA, 2021c). Although frequently mentioned, most studies do not explicitly define EoS, and how they could apply to the hydrogen market ramp-up remains unknown.

A strong negative correlation between experience and specific costs has already been observed for different electricity-generating technologies (Samadi, 2018). Looking at renewable energy technologies, costs have declined over time for most of them, and additional potential for technical advancements remains; this is expected to reduce costs further (IPCC, 2011). The electricity costs from utility-scale solar PV decreased by 85 % between 2010 and 2020 (IRENA, 2021b). In Germany, the price for a typical PV rooftop-system (10-100 kWp) fell by 92 % between 1990 and 2020 (Fraunhofer ISE, 2023). According to the Intergovernmental Panel on Climate Change (IPCC), these cost reductions resulted from an interaction of various drivers, like the upsizing of technologies, EoS, R&D, learning by using, learning by interacting, and market competition (IPCC, 2011).

The present study starts in chapter 2 by introducing the definition and economic fundamentals of EoS by discussing the concepts of internal EoS, external EoS, and negative EoS. In chapter 3, the internal EoS for hydrogen is assessed, thereby focusing on the production of hydrogen and the manufacturing of electrolyzers. Building on that, the potential for internal and external EoS is analyzed, and the concept of learning rates is introduced. Chapter 4 concludes with an overview of the main findings.

2 Economic Fundamentals of Economies of Scale

As shown in the previous chapter, the term EoS is widely used in the literature on hydrogen technologies and the hydrogen market. However, the concept of EoS is mostly treated superficially and cited as one reason for cost degressions without addressing the channels through which EoS are created. Thus, in the following, we will introduce the economic fundamentals of EoS and discuss how and why they work while distinguishing between internal and external EoS. Internal EoS refers to cost changes that a company achieves as it grows, while external EoS refers to cost changes for all participants within an industry caused by the growth of the industry and associated structures.

2.1 Internal Economies of Scale

Internal EoS describes the structures within a company that leads to the reduction of per-unit costs because of increasing the production volume. The company experiences increasing returns to scale, such that the increase in outputs is larger than the increased inputs. There are many ways and factors that drive internal EoS. Some of the main drivers are (Silberston, 1972):

- *Spread of fixed costs*: The fixed costs associated with producing the good are spread over a larger output, resulting in lower costs per unit.
- *Bulk purchasing*: A larger company can negotiate better prices for raw materials or other inputs due to larger order quantities.
- *Managerial* EoS: Larger companies benefit from specialization and division of labor among managers, and lower manager-to-production-worker inputs, resulting in reduced per-unit costs.
- *Financial* EoS: Larger companies have better access to capital and, therefore, better bargaining power over borrowing costs.
- *Marketing* EoS: Spreading advertising and promotional costs over larger output volumes decreases costs per unit.
- *Physical* EoS: Large companies have better capabilities to build optimal sizes of technical facilities. For example, the volume of a pipe increases quadratically with its diameter, but the materials used increase only linearly with its diameter.

Economic foundations Internal Economics of Scale

In the following, internal economies of scale are presented from an economic point of view, using equations and graphs. In mathematical terms, internal EoS can be expressed in the following way. First, consider $f(x_1, x_2)$ as a production function and (x_1, x_2) as input factors for producing a good. Then, π is a scalar that scales all input factors. Positive returns to scale are present if the following equation holds:

$$f(\pi * x_1, \pi * x_2) > \pi * f(x_1, x_2) \qquad (1)$$

For example, if the company doubles all its inputs, the output more than doubles. Therefore, the chosen input combination cannot be cost-optimal because the company could lower its costs - or increase its output by more than it increases its inputs - by exploiting these EoS. Thus, at the optimum, the following equation holds:

$$f(\pi * x_1^*, \pi * x_2^*) = \pi * f(x_1^*, x_2^*) \qquad (2)$$

In the previous equation, the produced output is optimal (indicated by the asterisk). If the company doubles all its inputs, it produces almost twice as much output. It cannot further reduce costs by changing the production volume. Like positive internal EoS, negative internal EoS can also occur, which means that average production costs increase with increasing production volumes.

$$f(\pi * x_1, \pi * x_2) < \pi * f(x_1, x_2) \qquad (3)$$

Figure 4 illustrates the relationship between average costs per unit $\mathbf{P}$ and the production scale $\mathbf{Q}$. At the function's minimum, the production scale is optimal, and the company cannot make additional profits (or decrease production costs) by increasing any input factor, analogously to equation 2. Therefore, in the optimum, the company produces output $\boldsymbol{Q^*}$ at the minimal costs of $\boldsymbol{P}*$.

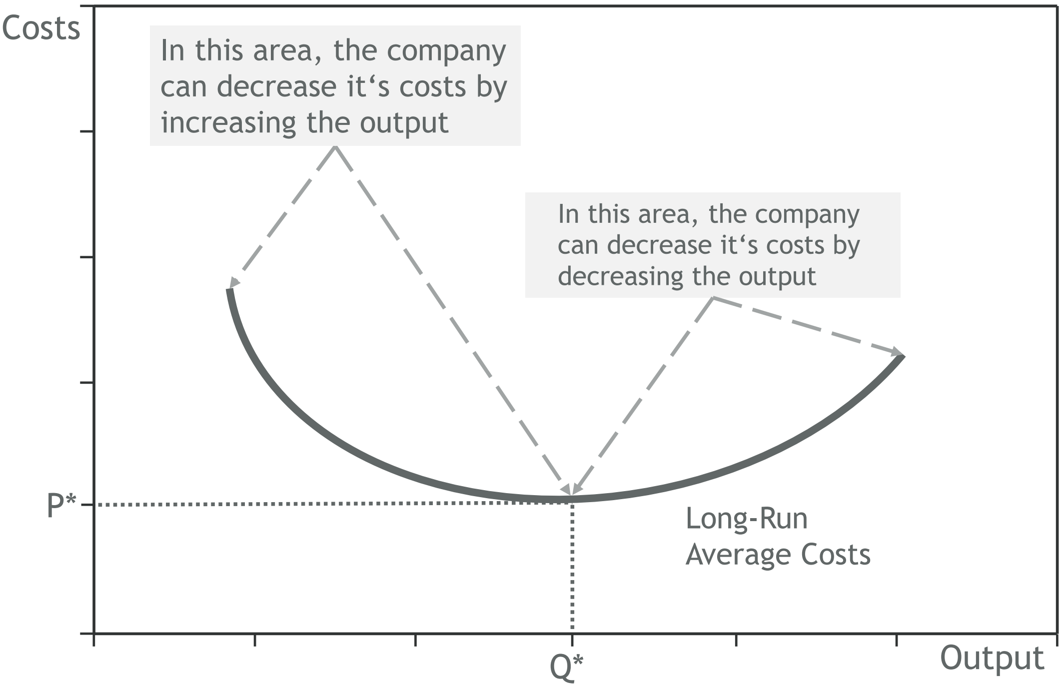

Figure 4: Internal Economies of Scale

Source: Own Illustration based on (Greenlaw et al., 2018)

The benefit of all the effects that lead to internal EoS lies within the decision-making power of the companies. During the market ramp-up of a commodity, the demand might not be high enough for companies to produce at an optimal scale. Therefore, the potential for cost reductions through internal EoS is typically the highest at the beginning of a market ramp-up.

2.2 External Economies of Scale

In contrast to internal EoS, external EoS occur if the industry grows. They may occur for a multitude of reasons. In the following, we illustrate three primary factors leading to positive external Economies of Scale.

Institutional Framework

The first factor that can generate external EoS is the institutional framework. For instance, a legal framework for handling specific goods or materials can prove advantageous for companies, as it endows investment security for those products. Nevertheless, implementing such a legal framework necessitates an industry of sufficient size to enable regulators to dedicate resources toward implementing such regulations. Therefore, the industry's size can encourage the development of supportive legal frameworks, reducing costs for individual companies.

Another instance refers to establishing associations representing individual companies and providing consultancy services. Such associations can perform critical roles, such as updating companies on legal frameworks, lobbying on behalf of companies, or providing information regarding relevant legislative matters. Once again, the larger the industry and the greater the number of companies operating in each sector, the more actors are represented by the association, reducing the cost of this service for each firm.

Lastly, monetary subsidies can drive down production costs, which increases production as demand is higher for lower prices. Given positive external economies of scale, subsidies can decrease production costs beyond the effect generated via the subsidization itself by generating external EoS.

Skills, Technology, and Knowledge

There are various ways in which skills contribute to the creation of EoS. A skilled workforce can lead to higher-quality goods and lower production costs. The generation of fundamental knowledge provided by the public sector, e.g., through universities or research institutes, can form the foundation for many private companies. When the public sector engages in fundamental research, the production costs of all companies decrease (Salter & Martin, 2001).

Further, companies that engage in advanced training activities to increase their workforce's skills and knowledge may reduce production costs. Due to spillovers, the entire industry can benefit from higher skills and knowledge within an individual company, so research and development within a single company can benefit the whole industry.

Finally, the specialization of suppliers can significantly lower the production costs of the final good, as labor division leads to the exploitation of economies of scale within an industry (McGee, 2015). However, specialization within value chains can only occur if the aggregated output is large enough and individual steps are required at a scale large enough for a company to specialize in that step. These aspects combined show how the growing of an industry decreases production costs for the industries' output through the channel of skills and knowledge.

Geographical Framework

There exist various geographical aspects that can create external EoS. This type of EoS occurs especially in areas where the costs associated with producing a particular good decrease regionally as the output within a specific region increases, regardless of who produces it.

Several factors contribute to geographical external EoS. For example, for goods transported via grid-based infrastructures, the costs of providing the infrastructure decrease with the number of users connected to the grid Costs decrease since marginal costs are negligible, and the high fixed costs of these infrastructures can be split among more individuals. This logic holds for transportation infrastructure such as streets, railways, and harbors for maritime transportation.

The concentration of production of a good in a particular region often leads to increased industry specialization, resulting in lower production costs for all companies involved. In these regions, specialized labor is easier to find (e.g., Silicon Valley).

The education system can adapt to meet regional labor requirements by providing specialized courses and training. Greater demand for specialized labor in a region can attract more such labor, allowing for greater labor mobility between companies and reducing labor costs. Lastly, the geographical density of the production of a good lead to amplified knowledge spillovers, which we identify as a thematic cluster regarding external EoS on its own.

Economic foundations External Economics of Scale

In mathematical terms, external EoS can be expressed in the following way. Suppose there exist companies $i, \dots, I$ producing the same good with the same production function f using the same inputs (x_1, x_2). The industry in market 1 then produces the aggregated output $F^1\ (i, \dots, I)$. When companies $n, \dots, N$ enter the industry in market 1, positive external EoS exist if the aggregated output grows by more than the aggregated output of companies $n, \dots, N$, operating in a separate market.

$$F^1(i, \dots, I, n, \dots, N) > F^1(i, \dots, I) + F^2(n, \dots, N). \tag{4}$$

If the opposite is true, negative external EoS are present. If the additional companies do not lead to positive or negative external EoS, then the following holds:

$$F^1(i, \dots, I, n, \dots, N) = F^1(i, \dots, I) + F^2(n, \dots, N). \tag{5}$$

Additionally, external EoS can occur if the initially existing companies increase their output, which would be equivalent to additional companies producing the same output, given the assumption of perfect competition and identical production functions is fulfilled. In other words, the source of external EoS is increased output which can stem from additional firms entering the market or increased production from existing firms.

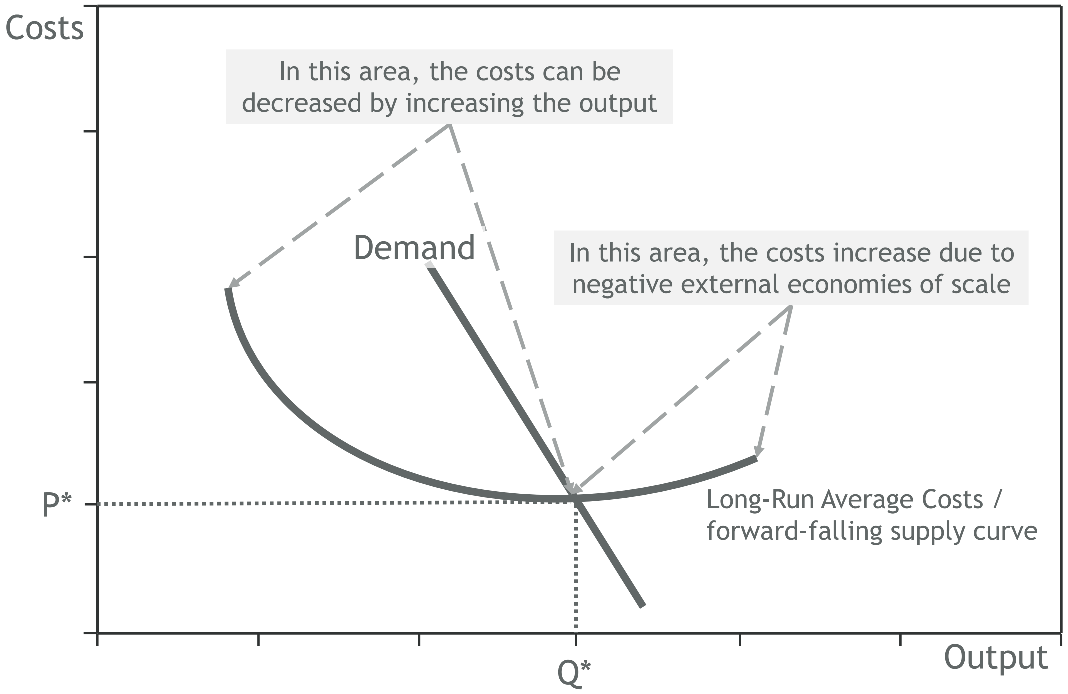

Figure 5: External Economies of Scale

Source: Own Illustration based on (Greenlaw et al., 2018)

Figure 5 illustrates the long-term average costs relative to the industry's aggregated output. The supply curve is downward sloping as long as price decreases for larger output quantities are possible (Greenlaw et al., 2018). With increased output, however, the average costs might increase due to negative external EoS. In the illustrated example, the price-quantity bundle Q^* and P^* is optimal and represents the markets equilibrium. The bundle coincides with the supply curves minimum because demand and supply intersect at that point.

However, it might also be the case that the equilibrium bundle is at a higher cost than the supply curves' minimum, as illustrated in Figure 6. In this case, the demand is too low to intersect the supply curve at the optimum, and therefore equilibrium prices are higher, and equilibrium outputs are lower compared to Figure 5. Even though, theoretically, costs could decrease if more output is produced, the industry would not scale up production as there is a lack of demand.

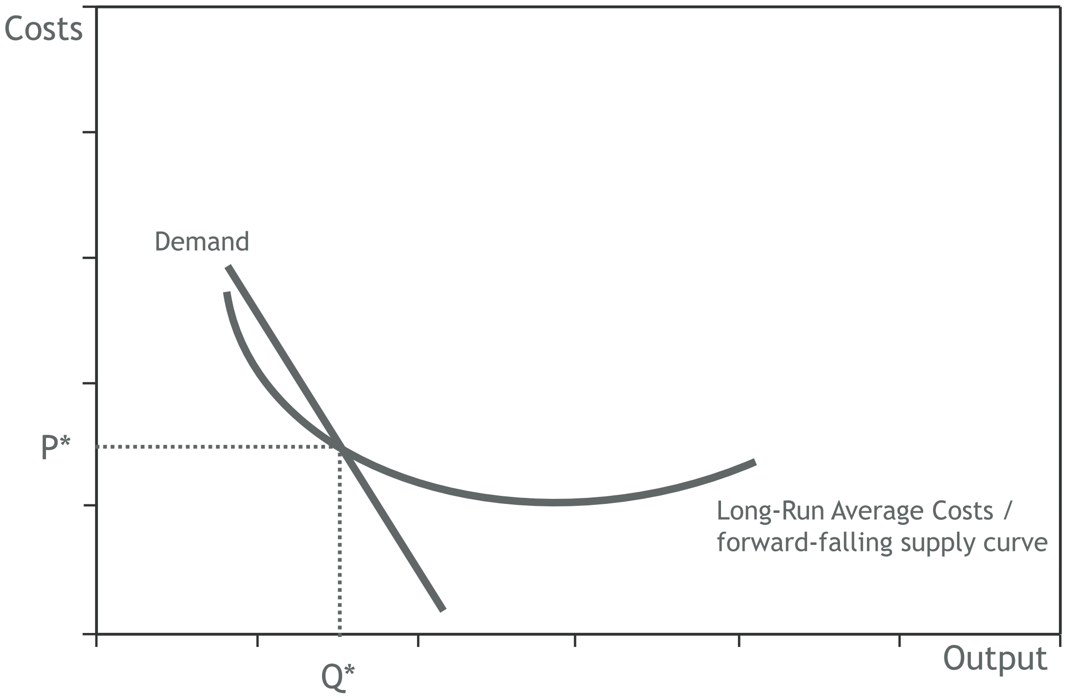

Figure 6: External Economies of Scale with low demand

Source: Own Illustration based on (Greenlaw et al., 2018)

Negative external Economies of Scale

External EoS can lead to an increase in average costs through various channels. This study investigates EoS within the hydrogen economy, which is at a very early stage of the market ramp-up. Therefore, negative external EoS are not to be expected to occur soon. For completeness, two important factors through which negative external EoS can occur are presented.

The **scarcity** of various input factors can force companies to produce with lower quality inputs, such as inferior raw materials, less-skilled labor supply, or non-ideal production sites. In the short term, the supply of many of these inputs is fixed, meaning that average costs increase as more companies produce the good with lower quality or higher cost inputs.

Increasing **environmental impacts** that have a negative impact on production processes makes production more expensive. For example, if more power plants use a river for cooling, this may mean that the river cannot be used for cooling by other power plants downstream due to possible overheating.

3 Economies of Scale in the Hydrogen Value Chain

The hydrogen value chain covers input production, hydrogen production, distribution, and utilization. Hydrogen can be used as an energy carrier or feedstock in numerous energy, industry, building, and transport applications. As mentioned earlier, various reports expect hydrogen production, distribution, and application to witness substantial cost reductions and point to a significant potential for EoS. Thus, the potential of internal and external EoS are discussed after introducing the hydrogen value chain. Furthermore, learning rates are introduced to show how EoS can be measured.

The Hydrogen Value Chain

Various hydrogen production processes do exist, as shown in Figure 7. Hydrogen can be produced from fossil fuels, e.g., natural gas and coal, or by water electrolysis with nuclear power or renewable energy sources (RES). In addition to hydrogen demand and production, the transportation infrastructure is crucial. A hydrogen infrastructure is needed to connect production and utilization if not produced on-site. Hydrogen can be transported in gaseous or liquid form via pipeline, ship, truck, or train. If there is a low temporal correlation between hydrogen production and demand, additionally to transport infrastructure also, hydrogen storage is necessary.

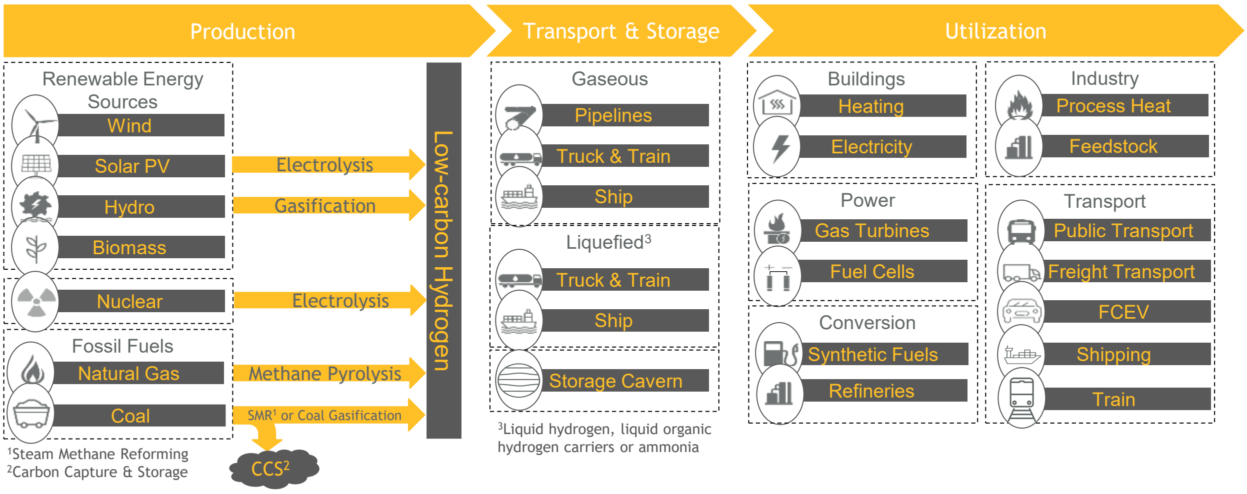

Figure 7: The hydrogen value chain

Source: Own illustration

3.1 Internal Economies of Scale in the Hydrogen Value Chain

Technology scaling offers the potential to gain internal (or plant-level) EoS. Thereby, internal EoS mainly exist in manufacturing production facilities for electrolyzers, the hydrogen production process, and hydrogen transportation.

3.1.1 Hydrogen Production

Hydrogen can be produced from various resources, including coal, natural gas, biomass, and water. The following analysis focuses on hydrogen production from fossil feedstocks and water electrolysis.

Hydrogen production from fossil feedstocks

Natural gas and coal are the most used feedstocks for hydrogen production. Hydrogen from natural gas is primarily produced by steam methane reforming of natural gas and water. The process requires heat, usually generated by the combustion of natural gas. The reforming reactions inherently produce CO_2. Hydrogen from natural gas accounted for 60 % of global hydrogen production in 2020 (IEA, 2021b).

Gasification is the primary process of producing hydrogen from coal by partially oxidizing coal with water. The combustion of coal usually covers the heat demand of the process. By its chemical reaction, coal gasification is inherently linked to CO_2 emissions. Coal gasification is a conventional process used since the 1800s. In Germany, industrially scaled coal gasification plants are not used today (Ahrens, 2016). However, in 2020 19 % of the global hydrogen was produced from coal (IEA, 2021b).

Figure 8 shows the hydrogen production costs of steam methane reforming and coal gasification as a function of the annual hydrogen production capacity of the plant and the coal and gas prices. The scale effects on investment costs of steam methane reforming and coal gasification are modeled by investment cost functions based on literature data or the seven-tenth rule (Couper et al., 2007):

$$\boldsymbol{Cost\ of\ plant\ B = cost\ of\ plant\ A\ \left(\frac{capacity\ of\ plant\ B}{capacity\ of\ plant\ A}\right)^{n}} \tag{6}$$

The exponent n ranges between 0.6 and 0.8 depending on the type of plant or equipment. A comparison between the cost reductions by feedstock price reductions and the cost reductions by increasing plant scale is helpful to bring the scale effects into context. Increasing the scale of the steam methane reformer from a small-scale plant (1 kt/yr) to a large-scale plant (1,000 kt/yr) brings a similar cost reduction as a decrease in natural gas prices by 20 USD/MWh. Likewise, increasing a coal gasification plant from small-scale to large-scale decreases the production costs in the same order of magnitude as a coal price decrease by 150 USD/t. The production costs of coal gasification are generally higher than those of steam methane reforming. Moreover, the cost reduction by scaling up the plant capacity is more significant for coal gasification than steam methane reforming.

Coal gasification processes solids, which is more CAPEX-intensive than steam methane reforming, which processes gas. Moreover, coal gasification requires pure oxygen, typically produced on-site in an air separation unit that is CAPEX-intensive, as well. The higher CAPEX intensity of coal gasification is why production costs are higher, and scale effects are stronger for coal gasification than steam methane reforming. Thus, coal gasification is more economical for large-scale plants.

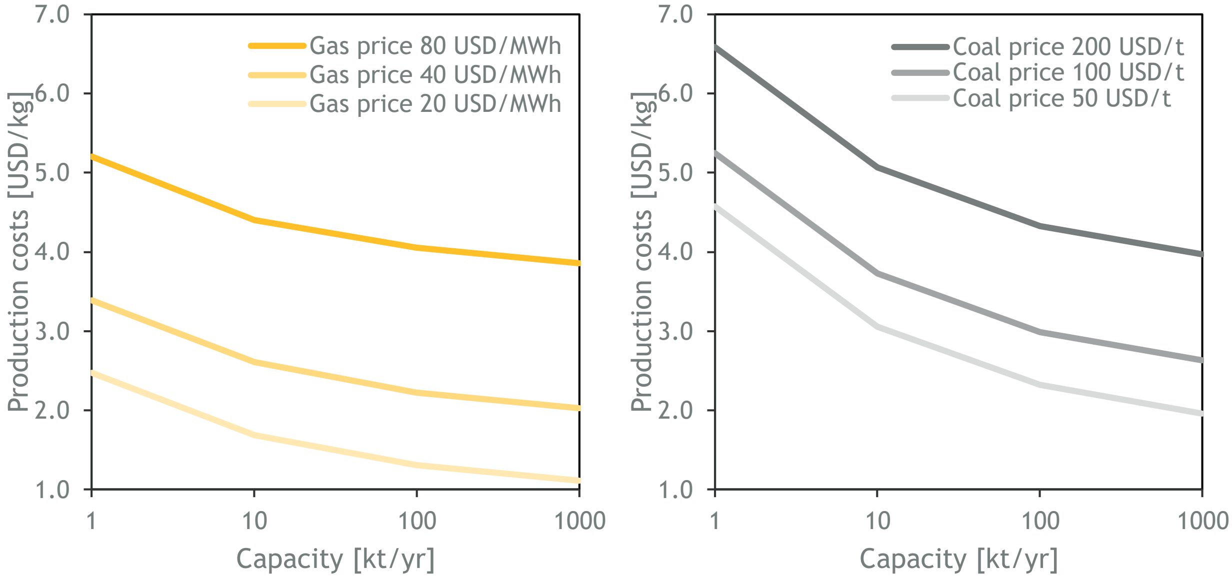

Figure 8: Hydrogen production costs from steam methane reforming (left) and coal gasification (right) as a function of the plant capacity and feedstock prices.

Source: Own calculations

Coal gasification processes solid materials, which is more CAPEX-intensive than steam methane reforming, which processes gas. Moreover, coal gasification requires pure oxygen, typically produced on-site in an air separation unit that is CAPEX-intensive, as well. The higher CAPEX intensity of coal gasification is why production costs are higher and scale effects are stronger for coal gasification than for steam methane reforming. Thus, coal gasification is only more economical for large-scale plants.

The GHG emissions of fossil hydrogen production can be decreased by carbon capture and storage (CCS). The removal of CO_2 from a flue gas stream is referred to as carbon capture. For steam methane reforming and coal gasification, pressure swing adsorption is the most economical technology for carbon capture (Hasan et al., 2014). The seven-tenth rule (see equation 6) estimates the scale effects of the investment costs of carbon capture plants and compressors (Couper et al., 2007). After carbon capture, the captured CO_2 is compressed up to 150 bar for transport and storage. At the storage site, the captured CO_2 is then sequestered underground. On a small-scale, CO_2 is transported in trailers via trucks or trains. If larger quantities are transported regularly on the same route, investing in a pipeline might be economically feasible, as pipeline transport is the most economical transport option on an industrial scale (Smith et al., 2021).

The specific costs of pipeline transport decrease with increasing flow rate, i.e., the pipeline's size assuming constant use. Figure 9 shows the specific pipeline transport costs of CO_2 dependent on the flow rate. Currently, CO_2 pipeline networks for large-scale deployment of CCS do not exist. Thus, new pipelines need to be built between CO_2 sources and sinks. For systems including more than one source and sink, the levelized costs of CO_2 transport can be reduced by forming pipeline networks. A simulative assessment of CCS networks in the USA found that pipeline networks can reduce the costs for transport and storage by up to 6.5 % compared to direct pipelines by increasing the pipelines' utilization and decreasing the overall pipeline length necessary (Kuby et al., 2011). These cost reductions through higher utilization of shared infrastructure are an example of external EoS.

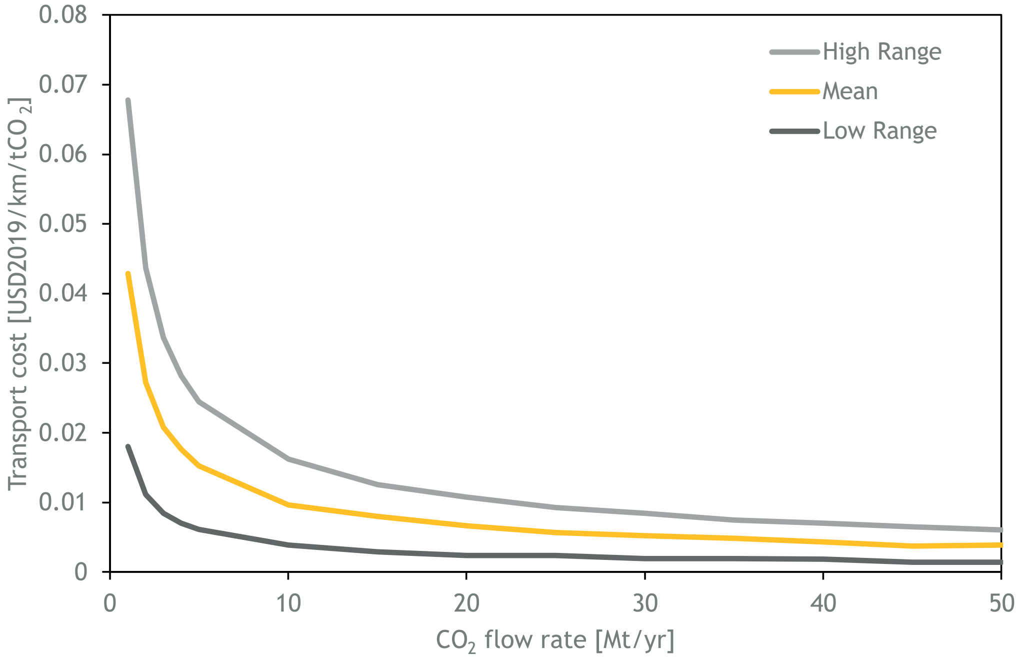

Figure 9: CO_2 pipeline transport costs in the USA.

Source: Own illustration based on (Smith et al., 2021)

Hydrogen production from water electrolysis

Water electrolysis is based on an endothermic redox reaction splitting water into hydrogen and oxygen, which requires electric power and heat. The hydrogen production potential of water electrolysis is immense since water is the only feedstock needed. Moreover, water electrolysis requires power and heat. The produced hydrogen is green if renewable energies cover the energy demand.

An electrolyzer system consists of several components. The center of the electrolyzer system is the electrolyzer stack, where the electrochemical reaction splitting of water into hydrogen and oxygen happens. Stack costs account for about half of the electrolyzers' total system costs. The stack does not show significant EoS since it is modular and is generally increased in number and not in size when scaling up the capacity of an electrolyzer system. However, the stack costs can be reduced by R&D or scale effects in stack manufacturing.

Next to the stack, the electrolyzer system consists of a balance of plant components, including gas processing, water conditioning, cooling, and power electronics. Depending on the scale, the balance of plant accounts for more than half of the electrolyzer system costs (IRENA, 2020). The costs of these components show EoS. For gas processing, water conditioning, and cooling, the investment cost over plant capacity can be estimated by the seven-tenth rule (see equation 6) (Turton et al., 2009). For instance, doubling the capacity of gas processing increases the investment costs of gas processing by only 62 %. The power electronics consist of a transformer and a rectifier converting high-voltage alternating current power from the grid to low-voltage direct current power needed for the stack. Costs for power electronics account for about half of the balance of plant costs (IRENA, 2020). Next to the stack, the electrolyser system consists of a balance of plant components, including gas processing, water conditioning, cooling, and power electronics. Depending on the scale, the balance of plant accounts for more than half of the electrolyser system costs (IRENA, 2020). The costs of these components show EoS. For gas processing, water conditioning, and cooling, the investment cost over plant capacity can be estimated by the seven-tenth rule (see equation 6) (Turton et al., 2009). For instance, doubling the capacity of gas processing increases the investment costs of gas processing by only 62 %. The power electronics consist of a transformer and a rectifier converting high-voltage alternating current AC power from the grid to low-voltage direct current DC power needed for the stack. Costs for power electronics account for about half of the balance of plant costs (IRENA, 2020).

The three major electrolysis technologies are alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and solid oxide electrolysis (SOEL) (Buttler & Spliethoff, 2018). Among these, AEL is the most mature and conventional technology for over a century (Barbir, 2005; IRENA, 2018). AELs are currently the most economical electrolyzers in terms of investment costs. The technology was initially designed for steady-state operation but has been further developed to allow flexible operation. PEMEL recently reached market readiness and is suited for a highly flexible operation. The investment costs of PEMEL are currently higher than those of AEL. Until 2050, investment costs for PEMEL and AEL are projected to converge and decrease by 60 to 85 % (IRENA, 2020). The SOEL technology is currently in the pilot stage.

In contrast to the other electrolysis technologies, SOEL can run as an electrolysis and fuel cell. The SOEL operates at high temperatures, which yields a higher efficiency but represents a less flexible operation than AEL and PEMEL (Buttler & Spliethoff, 2018). The flexibility of the electrolyzers is an advantage in an energy system based on volatile renewable energies, as more flexible electrolyzers can adjust to fluctuating electricity availability and prices.

Electrolysers manufacturing

Historically, electrolyzers were constructed in limited quantities for specific markets. In small-scale manufacturing, electrolyzers are often assembled manually since automation of the production process requires scale to bring economic benefits. Currently, electrolyzer manufacturing still entails much manual work. Scaling up an electrolyzer manufacturing plant, e.g., by building “gigafactories” which can produce electrolyzer capacity at gigawatt scale, might significantly reduce manufacturing costs through internal EoS. An increase in production volumes and larger unit sizes are expected to decrease the manufacturing costs for all electrolysis technologies (IRENA, 2021a).

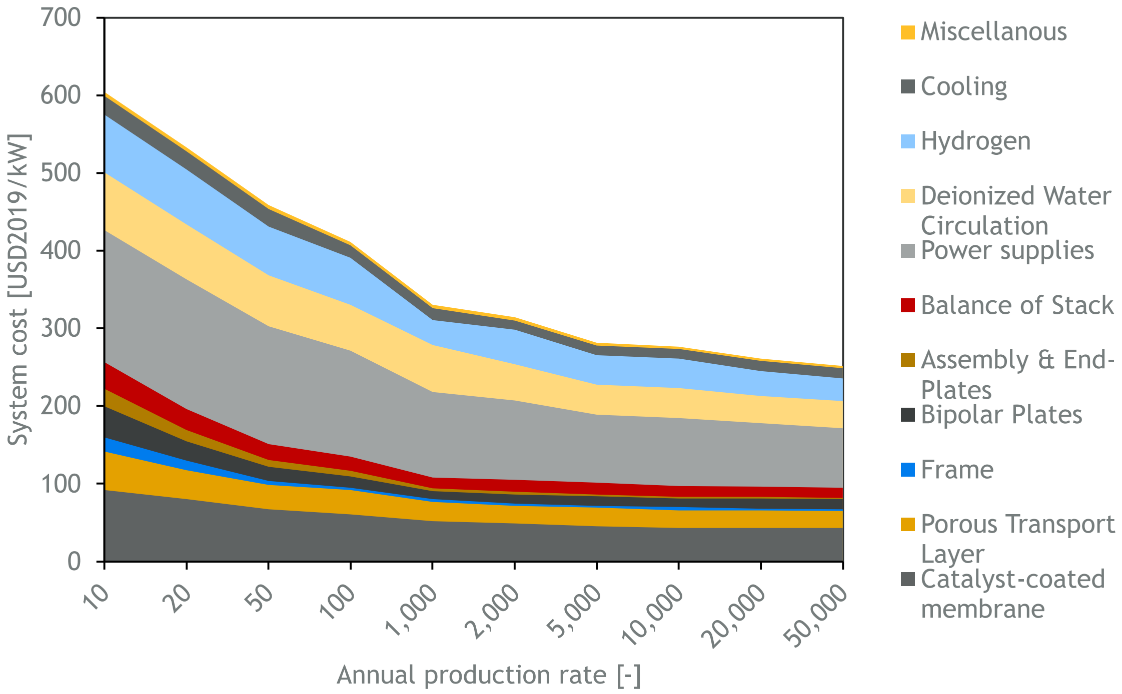

Figure 10: Manufacturing costs of a 1-MW_{el} PEM electrolyzer system over annual production rate

Source: Own illustration based on (Mayyas et al., 2019)

Internal EoS can be generated by automation of the manufacturing process, improvement of equipment utilization, and a decreasing share of building costs in total expenses. The streamlining of electrolyzers component supply chains is also expected to play a significant role in cost reductions. As an example of the EoS in electrolysers manufacturing, Figure 10 shows that the manufacturing costs of a 1 MW_{el} PEM electrolysers system decrease by 60 % if the annual production rate increases from 10 to 50,000 electrolyzer systems per year.As an example of the EoS in electrolyzer manufacturing, Figure 10 shows that the manufacturing costs of a 1 MW_{el} PEM electrolyzer system decrease by 60 % if the annual production rate increases from 10 to 50,000 electrolyzer systems per year.

Balance of plant costs accounts for about two-thirds of the total manufacturing costs. The manufacturing of balance of plant components is often outsourced to suppliers who produce them in large quantities for various markets and applications. Therefore, the cost reduction in scaling up production is less significant than stack manufacturing (National Renewable Energy Laboratory, 2019).

3.1.2 Hydrogen Transport

Hydrogen can either be transported as compressed gas or as a liquid. At ambient conditions, hydrogen is gaseous and has a volumetric energy density of 3.54 kWh/Nm^3 (referring to the lower heating value), which equals about a third of the volumetric energy density of natural gas. For small quantities, trailers are the most economical way to transport hydrogen. The transport in trailers is less economical than pipeline transport and, therefore, preferable for last-mile distribution or if the demand is low and sparsely distributed (Robinius et al., 2022).

Pipelines are the most economical way to transport large quantities of hydrogen across medium to large distances. Today, Europe and the United States have numerous insular hydrogen grid-connected sites in industrial clusters. There are two privately operated large industrial hydrogen grids in Germany, one in the Ruhr area and one in central Germany around Bitterfeld and Leuna (FfE, 2019).

Pipeline projects are capital-intensive. Over the lifetime of a pipeline, upfront investment costs typically account for over 90 % of total costs. Transportation in pipelines exhibits a physical economy of scale. A pipeline's throughput increases with the cross-section area πr^2 while a pipeline's cost of materials increases with the circumference $2\pi r$. Dividing the cross-section area (proportional to throughput) by circumference (proportional to costs of materials) gives 2/r, meaning that the unit investment costs decrease by 50 % if the pipeline radius doubles. Dividing the cross-section area (proportional to throughput) by circumference (proportional to materials costs) gives 2/r, meaning that the unit investment costs decrease by 50 % if the pipeline radius doubles. Figure 11 illustrates this relationship graphically.

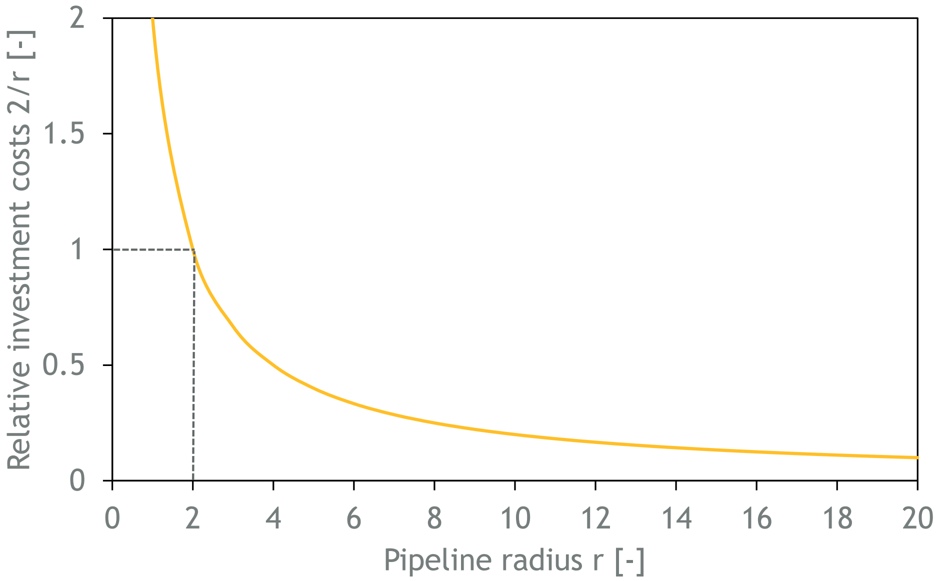

Figure 11: Relative investment costs of a pipeline in dependency of the pipeline radius

Source: Own illustration based on (Moritz et al., 2023)

Next to the pipe, a pipeline for gas requires compressors, generating pressure difference that keeps the gas flowing through the pipeline. Smaller compressors have higher unit costs per installed power than larger compressors (as the seventh-tenth rule applies). Regarding operational costs, larger pipelines tend to have lower pressure loss due to lower friction. Thus, larger pipelines require less energy per transported volume for compression (Molnar, 2022).

According to Figure 3, the demand for methane in Germany could decrease by 90 % in 2045. Consequently, many existing natural gas transport grid pipelines might no longer be needed to transport methane. These freed-up pipelines would thus be available for a switch to hydrogen. Hydrogen transport in existing natural gas pipelines is more cost-efficient than constructing new hydrogen pipelines (Kopp et al., 2022). When retrofitting existing pipelines from natural gas to hydrogen, various components, such as compressors and gas meters, must be replaced, but the pipelines can largely be reused (Nationaler Wasserstoffrat, 2021). According to the European transmission system operators, the costs for converting a pipeline from methane to hydrogen amount to approximately 20 % compared to the costs of constructing a new hydrogen pipeline (depending on the pipe diameter) (EHB, 2022).

For large-scale and long-distance hydrogen transport by ship, the low volumetric energy density of gaseous hydrogen is challenging. The density can be increased about 850-fold by liquefying the hydrogen. However, the value chain for liquid hydrogen, however, is characterized by high upfront investment costs and relatively small operating expenses, similar to long-distance gas pipelines. The investment costs include the liquefaction and regasification terminals and carrier vessels. Technically, transporting liquid hydrogen is similar to liquid natural gas (LNG). Thus, the EoS occurring in LNG transport might also apply to liquid hydrogen transport.

Analyzing data from Global Energy Monitor, 2022, we find that investment costs for LNG regasification and liquefaction terminals do not show significant scale effects. This might be due to the modular structure of such terminals (Global Gas Infrastructure Tracker, 2022). For instance, liquefaction terminals are often scaled up by building several parallel liquefaction trains instead of one large one. Thus, the scale effects are rather small. In contrast, LNG carrier Vessels show EoS. We find an upscaling factor of 0.5 for these vessels based on data from (Fikri et al., 2018; Thundersaidenergy, 2023).

A second option for increasing the density of hydrogen for transport is to bind hydrogen in liquid organic hydrogen carriers (LOHCs). LOHCs are unsaturated, aromatic carbon rings to which hydrogen can be bounded reversibly in a catalytic chemical reaction requiring heat.

A third option to increase the density of hydrogen is to convert hydrogen into a hydrogen-based molecule like ammonia, which can either be used as a product at the destination directly or can be reconverted into hydrogen (Reuß, 2019; Robinius et al., 2022).

3.2 External Economies of Scale in the Hydrogen Value Chain

Besides potential internal EoS, also external EoS could be achieved along the hydrogen value chain. Factors leading to external EoS can either stem from the institutional framework, skills, technology and knowledge, or the geographical framework (see chapter 2.2 and Figure 12). These groups can overlap as some factors have different dimensions, which can be clustered in multiple groups.

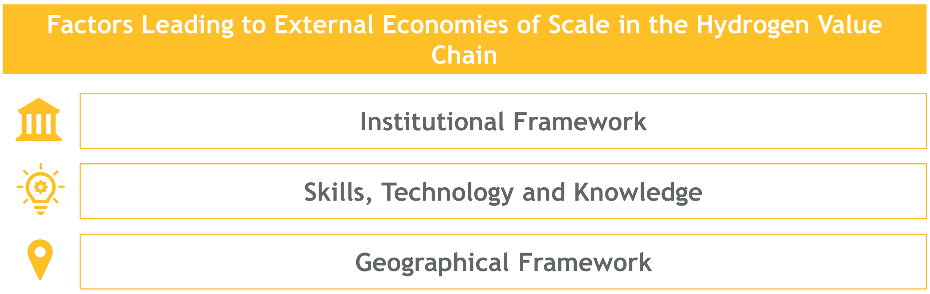

Figure 12: Factors leading to external EoS in the hydrogen value chain

Source: Own illustration

3.2.1 Institutional Framework

Various factors related to the institutional and policy framework of the hydrogen economy facilitate external EoS in the hydrogen value chain, thereby resulting in cost reductions.

Regulation, Standards, and Codes

A stable and supportive regulatory framework leads to investment security for businesses, which is needed to enable EoS. Governments and public authorities can support innovation and investments facilitating EoS by establishing a stable and supportive regulatory framework. This includes laws, regulations, technical standards and codes, Guarantees of Origin (GoO), internationally harmonized standards, and certification.

Technical standards can limit the variety of a product to a specific size and quality level, thereby achieving EoS (Tassey, 2000). An established framework of technical standards and codes can facilitate the commercialization of hydrogen technologies. Hydrogen standards are necessary to accelerate large-scale hydrogen 'solutions' ramp-up (European Clean Hydrogen Alliance, 2023).

To ramp-up the production and utilization of green hydrogen and its derivatives, a mechanism of GoO is needed. A GoO, documenting from which sources a given amount of hydrogen has been produced, ensures transparency about the renewable nature of hydrogen. A GoO forms the foundation of a certification scheme to verify the carbon footprint of hydrogen and thus ensure emission reduction. The legislator must ensure that the origin of green hydrogen can be proven to introduce supporting policy measures specifically directed at producing green hydrogen. Hydrogen producers need proof to validate the CO_2 emissions and potentially be remunerated for lower CO_2 emissions (IRENA, 2020). A GoO allows consumers to prove their share of renewable sources (EPICO Klimainnovation & Aurora Energy Research, 2022). A GoO for green hydrogen and derivatives is identified as an instrument for the hydrogen market ramp-up and decarbonization by the German national hydrogen strategy (Die Bundesregierung, 2020).

The European Union (EU) has started issuing legislation establishing renewable hydrogen criteria. As required in the Renewable Energy Directive (RED II), the EU defines under which circumstances hydrogen can be considered renewable in the EU. This is done by the first Delegated Act (Delegated regulation on Union methodology for RFNBOs) that lays down the criteria for hydrogen, hydrogen-based fuels, or other energy carriers to be considered as a renewable fuel of non-biological origin (RFNBO) (European Commission, 2023b). Additionally, the European Commission sets rules for the methodology of calculating greenhouse gas emissions (GHG) for RFNBOs (European Commission, 2023a).

Due to the international dimension of hydrogen trade and the commodity characteristics of hydrogen and derivatives, common standards and certification for the carbon intensity of hydrogen and hydrogen technologies are important (Deutsche Energie-Agentur GmbH (dena) & Weltenergierat – Deutschland e.V., 2022; European Parliamentary Research Service, 2021; IRENA & RMI, 2023).

Standards must be harmonized internationally for efficient international supply chains and cost reduction (Agora Energiewende & Guidehouse, 2021; Fraunhofer, 2019). Various initiatives and organizations play a role in the development of technical standards, e.g., *TÜV SÜD, International Organization for Standardization ISO/TC 197, International Electrochemical Commission (IEC TC 105)* and a certification scheme, e.g., *Hydrogen Energy Ministerial Meeting, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), CertifHy, Green Hydrogen Organisation (GH2)*. In its *Standardization Strategy,* the European Commission calls for "standards to support the roll-out of the clean hydrogen value chain" (European Commission, 2022). Until now, various initiatives have developed a certification for hydrogen, e.g., *CertifyHy certificates, Australian Clean Energy Regulator: Hydrogen Guarantee of Origin, Smart Energy Council: Zero Carbon Certification Scheme, Green Hydrogen Standard by GH2* (IRENA & RMI, 2023), but so far, no common approach or joint method to calculate hydrogen's CO_2 emissions has been established.

Supportive Institutions

Bringing together stakeholders, institutions, and organizations can represent a platform for exchanging knowledge and experience. This exchange can facilitate knowledge spillover and potentially spur cost reductions. When supportive institutions allow businesses to share resources, they enable EoS. Resources provided by institutions and organizations that businesses could share are, e.g., legal advice and access to information such as on new regulations or lobbying activities.

International organizations, national initiatives and platforms, industry associations, public institutions, and authorities focus on hydrogen. The increasing number of institutions and associations indicates that the hydrogen market ramp-up is progressing, and the potential to achieve external EoS through supportive institutions is increasing.

For instance, in the EU, the European Clean Hydrogen Alliance (ECH2A) brings together renewable and low-carbon hydrogen production, transport, storage, and demand in industry, mobility, and other sectors (European Commission, 2023d). ECH2A works on hydrogen standardization (European Clean Hydrogen Alliance, 2023).

The Fuel Cells & Hydrogen Observatory (FCHO) provides information and data on the hydrogen economy (FCHO, 2023). International organizations offer a platform for knowledge exchange and support the work towards common standards (IRENA, 2020).

On the international level, e.g., the IEA, with its technology collaboration programs (TCP), the International Renewable Energy Agentur (IRENA), and the Hydrogen Council, facilitate networking and sharing information.

In Germany, e.g., Deutscher Wasserstoff- und Brennstoffzellen-Verband e.V., Bundesverband der Energie- und Wasserwirtschaft (BDEW) or public initiatives such as Deutsche Industrie- und Handelskammer (DIHK) are working on improving the cooperation in various fields regarding hydrogen and its market ramp-up.

Policies

Also, policy instruments can support EoS (Timmons et al., 2015). Subsidies, for instance, can expand the production and utilization of hydrogen, thereby increasing learning rates. In China, industrial policies focusing on PV facilitated EoS and supported continuous innovation throughout the supply chain (IEA, 2022a).

Similarly to granting subsidies, governments can facilitate EoS and cost reductions for hydrogen by introducing tax incentives, e.g., by the reduction of taxes and duties on electricity used in hydrogen production, but also by mandatory quotas or de-risking mechanisms such as Carbon Contracts for Difference (CCfD) or Contracts for Difference (CfD), and CAPEX-subsidies (EWI, 2022; IRENA, 2021a).

3.2.2 Skills, Technology, and Knowledge

Skills, technology, and knowledge support positive external EoS in the hydrogen economy through various channels, such as R&D activities, skilled labor, education, training programs, and formal and informal knowledge spillover.

Research & Development

R&D activities are crucial to lower hydrogen technology costs. The greater the hydrogen economy, the more reasonable it is for public and private investors and society to allocate resources toward this sector. The payoff that companies can expect from investing in private research endeavors is related to the expected share of the market that can be taken over by taking the technological frontier. Meanwhile, advancing the technological frontier and thus taking over market shares benefits all consumers. Therefore, if market ramp-up leads to increased R&D activities through higher expected returns on investments in research, the market ramp-up becomes beneficial for all economic agents. Increased R&D activities are then to be expected both from the private sector and from the public sector.

Public R&D support, such as public funds, defining the research agenda, and attracting private investment, is important in reducing hydrogen costs (IEA, 2019). While public funds often focus on fundamental research, state funds and programs are additionally addressing the commercialization, cost reduction, and scale-up of hydrogen projects, e.g., by supporting pilot projects such as the 41 'important projects of common European 'interest' (IPCEI) on hydrogen (European Commission, 2023c).

Besides public R&D programs, private R&D is crucial for reaching EoS. While private and public investment in R&D can have identical objectives, private R&D spending often aims at cost reduction. Research on AEL and PEMEL is dominated by private funds focusing on competitive advantage to gain higher market shares (IRENA, 2020). For rather mature electrolysis technologies, like AEL and PEMEL, R&D focuses on reducing the use of scares materials, which is necessary for scaling up the manufacturing of electrolyzers. Reduced material usage decreases costs, enables sustainability, and increases the current supply (IRENA, 2020).

Skilled Labor

While hydrogen has been a niche technology for decades, with only a limited number of people having expertise on hydrogen, with growing political and economic attention, lately, the expertise and knowledge on hydrogen increased. This was also fostered by supportive institutions, organizations, platforms, and the media, serving as a platform for the arising political and public debate.

The availability of skilled labor can facilitate the hydrogen market ramp-up and EoS. At the same time, scaling up hydrogen technologies can result in the creation of skilled jobs (IEA, 2019). This is crucial as highly skilled labor is needed for a hydrogen market ramp-up. In Germany, the lack of a trained workforce adds additional pressure to the job market, which already faces the challenge of a shortage of specialists in branches other than the hydrogen market (DGB, 2021). While the general knowledge of hydrogen may have increased over the last few years, specific technical expertise on hydrogen is still missing. Experience in using and handling natural gas can be advantageous, as building on existing skills and capacities can be easier and cheaper than learning from scratch (IEA, 2019).

Specialized Training Programs

The specialized supply of education programs for the skills demanded by the industry leads to positive external EoS. Such programs can be offered, e.g., by schools, universities, public agencies, international organizations, or companies. Education and training of skilled workers require joint private and public forces. If the state finances workers' education, companies can cut spending on training, which facilitates EoS.

The private and public sectors already offer various programs focusing on hydrogen. In Germany, e.g., the Dresden International University has integrated useful modules into the curriculum of engineering students who want to focus on researching and working in the hydrogen economy. TÜV offers further education programs for engineers and other specialists, including skills for working with hydrogen products. The Inter-company Training Center in Eastern Bavaria gGmbH (ÜBZO) has developed hydrogen modules to be included in the existing German apprenticed professions system.

With the growth of the hydrogen economy, the number of training and education programs is expected to increase. Generally, these programs only get established when the economy is either already large enough or it is reasonable to assume it will soon be large enough. This so-called "chicken-egg problem" forms a challenge for growing markets. Without supply – here education programs – no demand – here workers with the intention to specialize – can be met, and without demand, no supply will be generated.

Knowledge Spillovers

It is expected that increased employment of specialized workers, and thus growing and broader expertise and knowledge, will produce formal and informal knowledge spillovers in the hydrogen economy. By increasing exchange between workers of different companies, discussions and exchange of best practices can result in new insights and ideas and potentially support innovation and technological advancements. These knowledge spillovers are beneficial for the hydrogen market ramp-up.

Knowledge spillover in the hydrogen economy can make production more productive, increase human capital, and increase the chance of creating new ideas. Consequently, start-ups that have the potential to make the whole industry more productive are more likely to evolve.

Knowledge spillover can be fostered through various channels, such as private interaction of specialized workers and dedicated events and formats. Regional, national, and international conferences focus on hydrogen, facilitating thematical exchange and thus knowledge spillover.

3.2.3 Geographical Framework

Geography and physical proximity can play a significant role in achieving EoS. The geographic framework can be manifested through the local concentration of different areas relevant to EoS, such as the emergence of specialized suppliers, the attraction of skilled workers, the construction of infrastructures, or the formation of hydrogen clusters.

Specialized Suppliers

When the components manufacturing for the hydrogen economy increases, companies can expect to specialize in increasingly small steps within the hydrogen value chain. In doing so, production costs decrease because of the usage of specialized technologies and especially trained and skilled workers. That can drive down costs for hydrogen significantly since companies do not have to be involved in incremental steps of the value chain, and their workers, too, can be trained and specialized for smaller increments of the value chain. The size of the economy highly drives the formation of specialized suppliers. Therefore, one can expect large external EoS through the specialization of suppliers within a growing hydrogen economy.

Skilled Workers

The potential to attract skilled workers for the hydrogen market may differ among regions. Regions with strong industrial structures or high renewable energy production may see an advantage here (DGB, 2021). Existing skills and capabilities, e.g., from grey hydrogen usage or handling natural gas, can be applied to developing hydrogen-specific skills, thereby resulting in a regional advantage through the potential of external EoS.

If companies produce similar goods or require similar skills within a region, the region provides a high supply of skilled workers necessary for these goods. Geographic clusters lead to the clustering of specially educated personnel, which increases the likelihood of knowledge spillovers. Companies in this region may also find it easier to attract skilled workers. In the medium term, the education system can adjust regionally to meet local demand for skilled labor by offering public or private educational and training programs in specific regions.

Infrastructure

The hydrogen market ramp-up is facing a "three-sided chicken-and-egg problem". Without a low-carbon hydrogen supply, there is no demand; without low-carbon hydrogen demand, there is no supply, and without a hydrogen transport infrastructure, trade is not possible. Thus, the transport infrastructure is a significant constraint to the market ramp-up.

For the hydrogen economy, relevant infrastructure not only comprises hydrogen pipelines but can also include, e.g., ports, roads, hydrogen fueling stations, the grid, water supply, or public transport for employees. Thereby, public but also private investment plays an important role. Infrastructure costs increase with the geographical distribution of producers, consumers, or companies.

Already today, clusters have been formed to meet the existing demand for grey hydrogen. Industrial parks are connected via pipelines to minimize hydrogen transport costs (Lambert & Schulte, 2021). Concentrating demand through clustering has the potential to significantly reduce the initial investment required for infrastructure (Ogden & Nicholas, 2011) as each additional user increases the flow rate, which makes the cost of pipeline infrastructure per unit of hydrogen decline (IRENA, 2021a). Major hydrogen pipeline projects, e.g., the European Hydrogen Backbone (EHB, 2022), focus on gradually connecting industrial clusters.

Hydrogen Cluster

By physically grouping hydrogen production and demand, hydrogen clusters, also known as hydrogen hubs, promise to facilitate positive network effects and EoS. Hydrogen clusters are a network of low-carbon hydrogen producers and consumers linked by transportation infrastructure. Geographic clusters offer short transportation distances, secure the hydrogen supply for industrial users, and thus the demand for low-carbon hydrogen for producers. This allows for less restrictive sizing of production facilities within the cluster and positive internal EoS.

Both governments and industry players understand the benefits of clustering hydrogen production and usage, so both are pursuing the creation of hydrogen and industry clusters. Public support and policies particularly address the formation of hydrogen clusters, e.g., the European Hydrogen Valleys Partnership of European regions.

Besides supporting the commercial usage of hydrogen in clusters, R&D efforts in clusters are supported. E.g., the cluster policy such as the Zukunftscluster-Inititiative (Clusters4Future) by the Federal Ministry of Economics and Climate (BMWK) and Federal Ministry of Education and Research (BMBF) aims at connecting science and economy to increase innovation and competitiveness (e.g., Hydrogen and Fuel Cell Initiative Hessen, Oldenburger Energiecluster OLEC e. V.). In addition to national measures, also regional and joint efforts are undertaken, e.g., the HC-H2, Helmholtz Cluster for Sustainable and Infrastructure-Compatible Hydrogen Economy supported by the BMBF and the federal state of North Rhine-Westphalia (NRW).

3.3 Learning Rates

As new technologies mature, they become more economical and efficient due to EoS. The learning rate is often used to determine the extent of the effects of EoS. It describes how technology costs decrease by a certain percentage when the total amount produced doubles (Lilliestam et al., 2020).

For renewable energies, significant cost reductions have been experienced. Internal EoS in the manufacturing of RE-technologies and the plant size has, among others, resulted in declining RE-costs. In particular, the costs for PV have declined significantly over the past decades. Costs for materials, labor, operation & maintenance, electricity, and plant and equipment depreciation determine the PV manufacturing costs. The plant size determines various of these costs. Costs for electricity, labor, maintenance, and depreciation are expected to scale economies with increasing plant size (Kavlak et al., 2018). Larger units (e.g., larger wind turbines) offer EoS by reducing installation costs, project development costs, and O&M costs (IRENA, 2021b).

Infobox: Technology Readiness Level

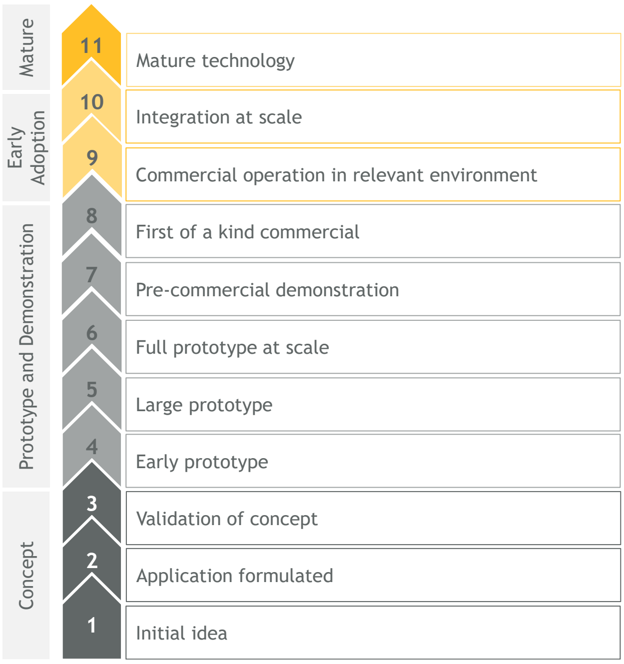

Figure 13: Technology Readiness Level

Source: Own illustration based on (IEA, 2021a)

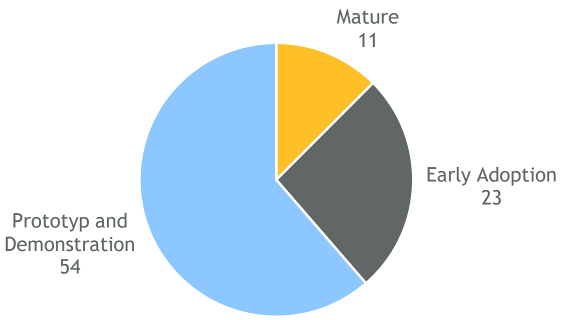

Figure 14: Stages of Technology Readiness Level of hydrogen technologies

Source: Own illustration based on (IEA, 2022a)

New technologies, such as hydrogen technologies, go through different stages of the development process. This process is typically time-consuming, starting from the concept development to a prototype and, finally, the demonstration at scale, adoption, and commercialization (IEA, 2021a).

The level of development of new technologies can be assessed using the Technology Readiness Level (TRL) scale 1 to 11 (see Figure 13). This scale allows the maturity of different technologies to be compared. Additionally, the TRL indicates the scale at which technology is deployed. With a TRL 1-3, only the idea and conceptualization of the technology exists so far. Technologies with a TRL 4-6 are in the development phase, where prototypes are tested, for example. A TRL 7-8 comprises the demonstration phase. In TRL phases 9-10, technologies are commercially deployed. In this stage, some designs have reached the market.

Nevertheless, policy support remains required for scale-up. At TRL 11, technology is mature. This includes commercial technologies which have reached sizable deployment. Thereby the potential for technological improvement is almost depleted. Only minor innovation is still expected for these technologies (IEA, 2021a). Only technologies with a high TRL scale become possible.

Positive internal and external EoS can occur along the entire TRL scale. While in the early TRL stage, mainly public spending may be used, the private sector dominates higher TRL spending.

Different technologies of the hydrogen value chain are at different stages of technology readiness (see Figure 14 and Figure 15). While some technologies, such as ammonia tankers and aboveground physical storage, are already mature, many technologies are in the stage of early adoption, e.g., new hydrogen pipelines, PEMEL, and ALE. The TRL of many end-use technologies is often still at the stage of demonstration and prototype (see Figure 14) (IEA, 2022b).

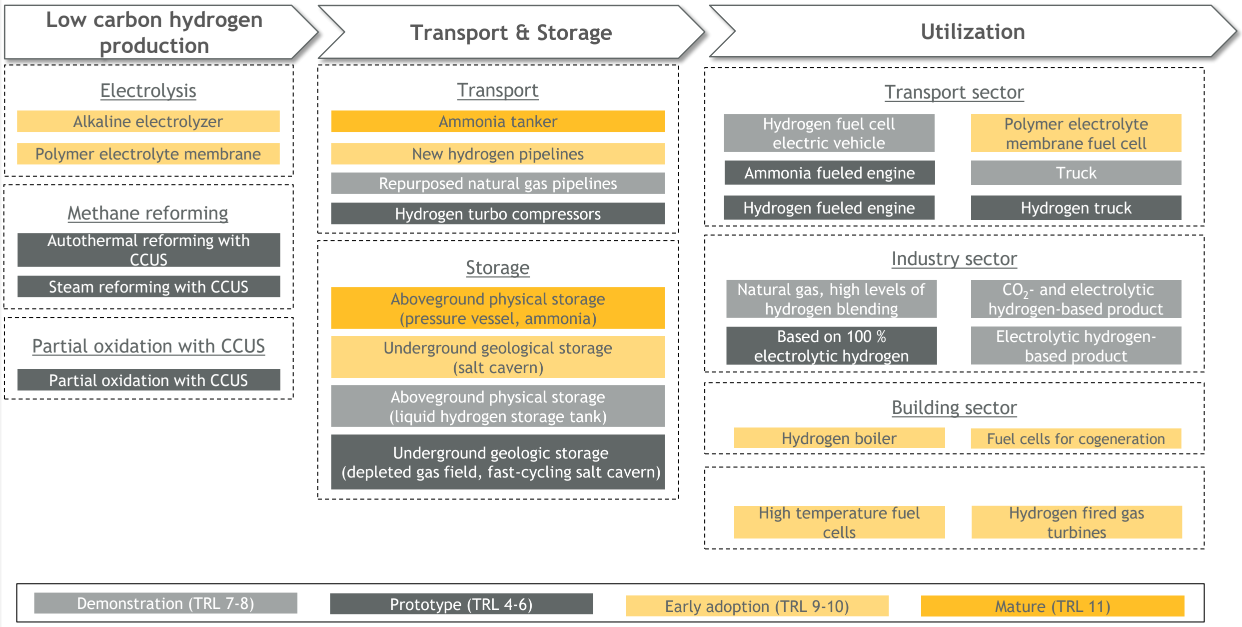

Figure 15: Technology Readiness Level of selected technologies along the hydrogen value chain

Source: Own illustration based on (IEA, 2022a)

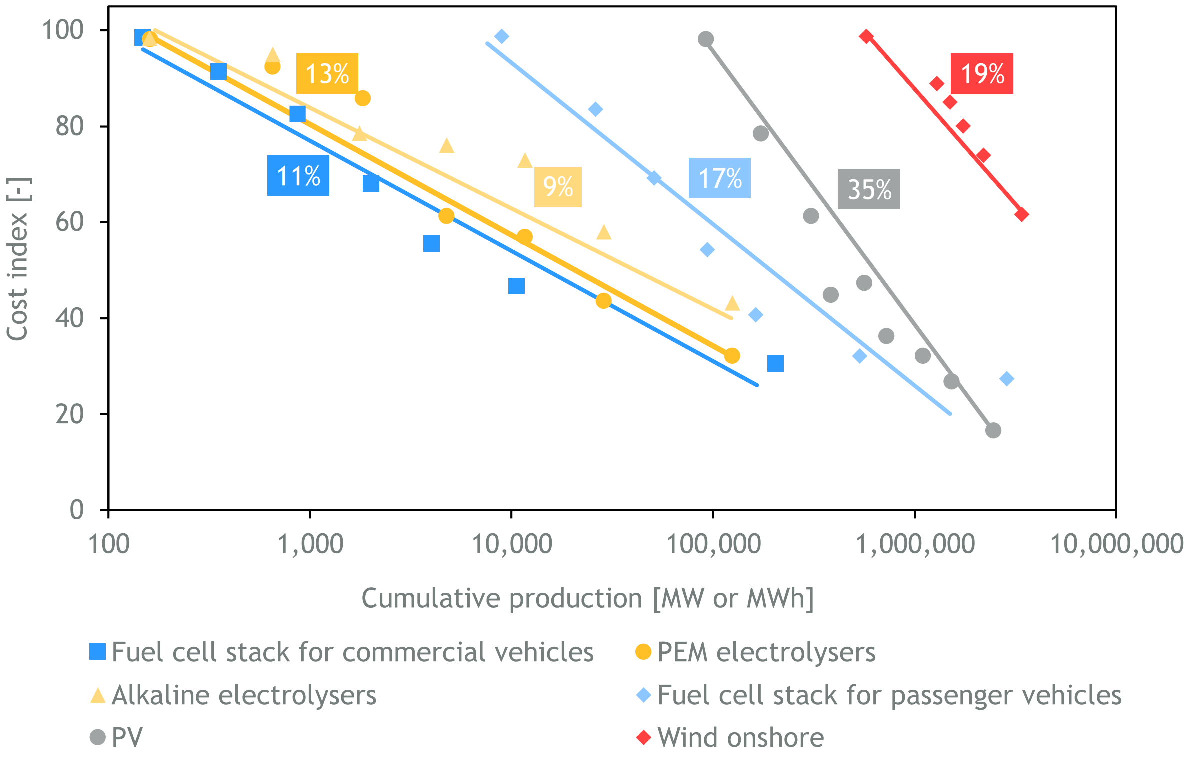

Figure 16: Learning rates for system CAPEX of hydrogen technologies (electrolysers and fuel cells) and comparative technologies (PV and onshore wind turbines).

Data labels show the learning rates in percent.

Source: Own illustration based on (Hydrogen Council, 2020)

According to Figure 16, the learning rates for fuel cells and electrolyzers range from 9 % to 14 %. Some studies also assess higher learning rates of up to 21 % (IRENA, 2020). However, the expected learning rates of electrolyzers are notably lower than the 35 % learning rates that have been observed in the PV industry over the past decade.

Like EoS for manufacturing, where the cost reduces unevenly over scale, the learning rates also change with the cumulated quantity produced. Components with higher learning rates will constitute a smaller proportion of the total cost as the cumulated produced quantity increases because their cost reduction is more significant than those with a lower learning rate. The differences in learning rates can be substantial depending on the component. For instance, a research paper suggests that learning rates are 18 % for membrane manufacturing but only 8 % for the stack assembling of a PEMEL (Böhm et al., 2019).

4 Conclusion

In this study, we discussed the concept of EoS divided into internal and external effects. Internal EoS are cost reductions achieved by an individual company as it grows. External EoS are cost reductions for all companies. The source is the growth of the industry and the structures that are associated with it.

Furthermore, potential internal EoS in the hydrogen value chain, comprising supply, infrastructure, and utilization, were discussed. We showed that internal EoS can be expected mainly with hydrogen production and transport. While in fossil-based hydrogen production, coal gasification shows greater internal EoS than steam methane reforming, for water electrolysis, there is only negligible EoS expected. In contrast, the manufacturing of electrolyzers shows great potential for cost reductions through internal EoS, as today's production is mainly manual work and could profit from industrialization.

When looking at external EoS, it is not possible to discuss specific parts of the hydrogen value chain, as external EoS is generated by the hydrogen economy as a whole. Therefore, we discussed many potential external EoS through the institutional framework, skills, technology and knowledge, and the geographical framework. It was shown that there is a large potential for external EoS in all areas, and thus cost reductions are possible. As the hydrogen market ramp-up is still at the very beginning, many areas are developing fast, and some are still in the early stages.

Public actors have major potential to facilitate EoS and cost reduction for hydrogen. Especially in the early stage of the hydrogen market ramp-up, the legal and regulatory framework can influence various factors that support EoS along the hydrogen value chain. Governments and public authorities can strengthen various factors leading to external EoS, including the institutional framework, skills, and geographical framework.

- Governments can facilitate EoS by introducing a stable and supportive **regulatory and policy framework**. A limited or non-existing regulatory framework, a lack of standards and codes, and the missing harmonized certification system highlight the niche role technologies have been playing so far.
- With public funding and programs directed at **R&D** focusing on hydrogen technologies, the state can push for technology advancement and cost reduction. Thus, in the mid-to-long run, the TRL of hydrogen technologies increases, which makes commercialization and application at scale of until now immature technologies possible.
- The state can finance or establish **supportive institutions** that allow businesses to share resources and reduce costs. These supportive institutions, platforms, and roundtables introduced by public authorities can accelerate formal and informal **knowledge spillover.**
- The state and public entities play an important role in offering or financing relevant educational and training programs, thereby advancing **skills** on hydrogen.

Besides public activities and measures, private activities are important in achieving EoS in the hydrogen value chain.

References

Agora Energiewende, & Guidehouse. (2021). *Making renewable hydrogen cost-competitive: Policy instruments for supporting green H₂*. https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf

Ahrens, R. (2016, July 8). Braunkohle wird zu Synthesegas. *VDI Nachrichten*. https://www.vdi-nachrichten.com/technik/umwelt/braunkohle-wird-zu-synthesegas/

Barbir, F. (2005). PEM electrolysis for production of hydrogen from renewable energy sources. *Solar Energy*, *78*(5), 661–669. https://doi.org/10.1016/j.solener.2004.09.003

Böhm, H., Goers, S., & Zauner, A. (2019). Estimating future costs of power-to-gas – a component-based approach for technological learning. *International Journal of Hydrogen Energy*, *44*(59), 30789–30805. https://doi.org/10.1016/j.ijhydene.2019.09.230

Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440–2454. https://doi.org/10.1016/j.rser.2017.09.003

Couper, J. R., Hertz, D. W., & Smith, F. L. (2007). Process Economics. In *Perry’s Chemical Engineers’ Handbook (8th Edition)* (8th ed.). McGraw-Hill Professional Publishing.

dena. (2019). *Dialogprozess Gas 2030: Hintergrundpapier*. https://www.prognos.com/sites/default/files/2021-01/hintergrundpapier_dialogprozess_gas_2030.pdf

Deutsche Energie-Agentur GmbH (dena), & Weltenergierat – Deutschland e.V. (2022). *Global Harmonisation of Hydrogen Certification: Overview of global regulations and standards for renewable hydrogen*. https://www.weltenergierat.de/wp-content/uploads/2022/01/dena_WEC_Harmonisation-of-Hydrogen-Certification_digital_final.pdf

DGB. (2021). *Trade union demands for the hydrogen economy: Towards an H2-ready work-force*. https://www.dgb.de/uber-uns/dgb-heute/struktur-industrie-und-dienstleistungspolitik/energiepolitik/++co++d24014f4-1f63-11ec-8f6f-001a4a160123

Die Bundesregierung. (2020). *Die Nationale Wasserstoffstrategie*. https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=1

EHB. (2022). *European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Concerning 28 Countries*. https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries.pdf

EPICO Klimainnovation, & Aurora Energy Research. (2022). *Guarantees of Origin for Green Energy: Granular Green Electricity Certification for a Marketbased Energy Transition*. https://www.kas.de/documents/252038/16166715/Guarantees+of+Origin+for+Green+Energy.pdf/e40eb8d2-6e83-5411-aa9c-ab1b888f4e2f?version=1.0&t=1663249143008

European Clean Hydrogen Alliance. (2023). *Roadmap on Hydrogen Standardisation*. https://hydrogeneurope.eu/wp-content/uploads/2023/03/2023-03-01_ECH2A-ROADMAP-on-Hydrogen-Standardisation-.pdf

European Commission. (2022). *An EU Strategy on Standardisation Setting global standards in support of a resilient, green and digital EU single market*. https://ec.europa.eu/docsroom/documents/48598

European Commission. (2023a). *Delegated regulation for a minimum threshold for GHG savings of recycled carbon fuels and annex*. https://energy.ec.europa.eu/publications/delegated-regulation-minimum-threshold-ghg-savings-recycled-carbon-fuels-and-annex_en

European Commission. (2023b). *Delegated regulation on Union methodology for RFNBOs*. https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

European Commission. (2023c). *IPCEIs on hydrogen*. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en

European Commission. (2023d, May 9). *European Clean Hydrogen Alliance*. https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance_en

European Parliamentary Research Service. (2021). *EU hydrogen policy: Hydrogen as an energy carrier for a climate-neutral economy*. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI(2021)689332_EN.pdf

EWI. (2022). *H_2—Förderkompass: Kriterien und Instrumente zur Förderung von Wasserstoffanwendungen für den Markthochlauf*. https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2023/02/220425_EWI_H2_Foerderkompass.pdf

EWI. (2023). *Datengrundlage für die E.ON H2Bilanz 2023: Begleitdokument zur Einordnung der Ergebnisse*. https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2023/04/230421_EWI_Begleitdokument_Datengrundlage_H2Bilanz_02-2023.pdf

FCHO. (2023). *Welcome to the Fuel Cells & Hydrogen Observatory*. https://www.fchobservatory.eu/

FfE. (2019). *Studie zur Regionalisierung von PtG-Leistungen für den Szenariorahmen NEP Gas 2020-2030*.

Fikri, M. H. C., Hendrarsakti, J., Sambodho, K., Felayati, F. M., Octaviani, N. S., Giranza, M. J., & Hutomo, G. A. (2018). *Estimating Capital Cost of Small Scale LNG Carrier*. *Proceedings of the 3rd International Conference on Marine Technology*, 225–229.

Fraunhofer. (2019). *A Hydrogen Roadmap for Germany*. https://www.fraunhofer.de/content/dam/zv/de/ueber-fraunhofer/wissenschaftspolitik/Positionen/2019-10-a-hydrogen-roadmap-for-germany.pdf

Fraunhofer ISE. (2023). *Photovoltaics Report*. https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html

Global Gas Infrastructure Tracker. (2022). *Global Gas Infrastructure Tracker*. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

Greenlaw, S. A., Shapiro, D., & Taylor, T. (2018). *Principles of microeconomics* (2e. Revision number ME2-2017-001-(03/18)-LC). OpenStax, Rice University.

Hasan, M. M. F., Boukouvala, F., First, E. L., & Floudas, C. A. (2014). Nationwide, Regional, and Statewide CO $_2$ Capture, Utilization, and Sequestration Supply Chain Network Optimization. *Industrial & Engineering Chemistry Research*, *53*(18), 7489–7506. https://doi.org/10.1021/ie402931c

Hydrogen Council. (2020). *Path to hydrogen competitiveness: A cost perspective*. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

IEA. (2019). *The Future of Hydrogen: Seizing today's opportunities*. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

IEA. (2021a). *Energy Technology Perspectives 2020*. https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf

IEA. (2021b). *Global Hydrogen Review*. https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf

IEA. (2021c). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

IEA. (2022a). *Special Report on Solar PV Global Supply Chains*. https://iea.blob.core.windows.net/assets/4eedd256-b3db-4bc6-b5aa-2711ddfc1f90/SpecialReportonSolarPVGlobalSupplyChains.pdf

IEA. (2022b). *ETP Clean Energy Technology Guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedCCTag=Hydrogen&trlRange=9-10

IPCC. (2011). *Special Report on Renewable Energy: Sources and Climate Change Mitigation*. https://archive.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf

IRENA. (2018). *Hydrogen from renewable power: Technology outlook for the energy transition*. https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf

IRENA. (2020). *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5C Climate Goal*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2021a). *Green hydrogen supply: A guide to policy making*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Green_Hydrogen_Supply_2021.pdf?rev=f24d7919eee5433e86ae9dbc4cf10218

IRENA. (2021b). *Renewable Power Generation Costs in 2020*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

IRENA, & RMI. (2023). *Creating a global hydrogen market: Certification to enable trade*. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jan/IRENA_Creating_a_global_hydrogen_market_2023.pdf?rev=cad6962f55454a46af87dec5f2e6c6e8

Kavlak, G., McNerney, J., & Trancik, J. E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, *123*, 700–710. https://doi.org/10.1016/j.enpol.2018.08.015

Kopp, J., Moritz, M., Scharf, H., & Schmidt, J. (2022). Strukturwandel in der Gaswirtschaft – Was bedeutet die Entwicklung der Gas- und Wasserstoffnachfrage für die zukünftige Infrastruktur?: Eine Metaanalyse bestehender Energiesystemstudien. *Zeitschrift für Energiewirtschaft*. https://doi.org/10.1007/s12398-022-00335-2

Kuby, M. J., Middleton, R. S., & Bielicki, J. M. (2011). Analysis of cost savings from networking pipelines in CCS infrastructure systems. *Energy Procedia*, *4*, 2808–2815. https://doi.org/10.1016/j.egypro.2011.02.185

Lambert, M., & Schulte, S. (2021). *Contrasting European hydrogen pathways: An analysis of differing approaches in key markets*. The Oxford Institute for Energy Studies.

Lilliestam, J., Melliger, M., Ollier, L., Schmidt, T. S., & Steffen, B. (2020). Understanding and accounting for the effect of exchange rate fluctuations on global learning rates. *Nature Energy*, *5*(1), 71–78. https://doi.org/10.1038/s41560-019-0531-y

McGee, J. (2015). Economies of Scale. In C. L. Cooper (Ed.), *Wiley Encyclopedia of Management* (pp. 1–6). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118785317.weom120226

Molnar, G. (2022). Economics of Gas Transportation by Pipeline and LNG. In M. Hafner & G. Luciani (Eds.), *The Palgrave Handbook of International Energy Economics* (pp. 23–57). Springer International Publishing. https://doi.org/10.1007/978-3-030-86884-0_2

National Renewable Energy Laboratory. (2019). *Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers*. https://www.nrel.gov/docs/fy19osti/72740.pdf

Nationaler Wasserstoffrat. (2021). *Wasserstofftransport*. https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/2021-07-02_NWR-Grundlagenpapier_Wasserstofftransport.pdf

Ogden, J., & Nicholas, M. (2011). Analysis of a “cluster” strategy for introducing hydrogen vehicles in Southern California. *Energy Policy*, *39*(4), 1923–1938. https://doi.org/10.1016/j.enpol.2011.01.005

Prognos. (2020). *Kosten und Transformationspfade für strombasierte Energieträger: Endbericht zum Projekt "Transformationspfade und regulatorischer Rahmen für synthetische Brennstoffe“*. https://www.bmwk.de/Redaktion/DE/Downloads/Studien/transformationspfade-fuer-strombasierte-energietraeger.pdf?__blob=publicationFile

Prognos, Öko-Institut, & Wuppertal Institut. (2021). *Klimaneutrales Deutschland 2045: Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann*. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_231_KNDE2045_Langfassung_DE_WEB.pdf

Reuß, M. (2019). Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur. *Energie & Umwelt /Energy & Environment*, *467*. https://publications.rwth-aachen.de/record/765438/files/765438.pdf

Robinius, M., Cerniauskas, S., Madlener, R., Kockel, C., Praktiknjo, A., & Stolten, D. (2022). Economics of Hydrogen. In M. Hafner & G. Luciani (Eds.), *The Palgrave Handbook of International Energy Economics* (pp. 75–102). Springer International Publishing. https://doi.org/10.1007/978-3-030-86884-0_4

Salter, A. J., & Martin, B. R. (2001). *The economic benefits of publicly funded basic research: A critical review*.

Samadi, S. (2018). *The experience curve theory and its application in the field of electricity generation technologies – A literature review*.

Silberston, A. (1972, March). Economies of Scale in Theory and Practice. *The Economic Journal Oxford University Press on Behalf of the Royal Economic Society*, 369–391.

Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., & Paltsev, S. (2021). The cost of CO2 transport and storage in global integrated assessment modeling. *International Journal of Greenhouse Gas Control*, *109*, 103367. https://doi.org/10.1016/j.ijggc.2021.103367

SPD, FDP, & Bündnis 90 / Die Grünen. (2021). *Mehr Fortschritt wagen: Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit*. https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag_2021-2025.pdf

Tassey, G. (2000). Standardization in technology-based markets. *Research Policy*, *29*(4–5), 587–602. https://doi.org/10.1016/S0048-7333(99)00091-8

Thundersaidenergy. (2023). *LNG transport: Shipping economics?* [Data set]. https://thundersaidenergy.com/downloads/lng-transport-shipping-economics/

Turton, R., Bailie, R. C., Whiting, W. B., & Shaeiwitz, J. A. (Eds.). (2009). *Analysis, synthesis, and design of chemical processes* (3rd ed). Prentice Hall.

List of Abbreviations

AEL	Alkaline electrolysis
BDEW	Bundesverband der Energie- und Wasserwirtschaft
BMBF	Federal Ministry of Education and Research
BMWK	Federal Ministry of Economics and Climate
CAPEX	Capital expenditures, capital expenditures
CCfD	Carbon Contracts for Difference, Carbon Contracts for Difference
CCS	Carbon capture and storage, carbon capture and storage
CfD	Contracts for Difference, Contracts for Difference
Clusters4Future	Zukunftscluster-Inititiative
dena	Deutsche Energie-Agentur GmbH
DIHK	Deutsche Industrie- und Handelskammer
ECH2A	European Clean Hydrogen Alliance
EoS	Economies of Scale
EU	European Union
FCHO	Fuel Cells & Hydrogen Observatory
GH2	Green Hydrogen Organisation
GHG	Greenhouse gas
GoO	Guarantees of Origin, Guarantees of Origin
HC-H2	Helmholtz Cluster for Sustainable and Infrastructure-Compatible Hydrogen Economy
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important projects of common European interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LNG	Liquid natural gas
LOHCs	Liquid organic hydrogen carriers
NRW	North Rhine-Westphalia
NZE	Net Zero Emissions
OLEC	Oldenburger Energiecluster
OPEX	Operational expenditures
PEMEL	Proton exchange membrane electrolysis
R&D)	Research and development
RED II	Renewable Energy Directive
RES	Renewable energy sources
RFNBO	Renewable fuel of non-biological origin
SOEL	Solid oxide electrolysis
TCP	Technology collaboration programs
TRL	Technology Readiness Level
ÜBZO	Inter-company Training Center in Eastern Bavaria gGmbH

List of Figures