Friedrich-Alexander-Universität
Technische Fakultät

Hydrogen Refueling System for Heavy-duty Vehicles – Process Optimization and Centralization

CBI project course spring 2023

Cooperation with: Framatome GmbH Covalion, Erlangen

The project course is a compulsory module without commercial interests for students of the Department of Chemical and Bioengineering (CBI) at the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) in cooperation with a partner from industry. In this year's spring course, the partner was **Covalion**, a brand of Framatome, located in Erlangen, Germany. The aim was to plan a **hydrogen refueling system** for heavy-duty vehicles in which the hydrogen is produced on site by an electrolyzer.

The boundary conditions were: 1 t of hydrogen daily for refueling 40 buses with 30 kg in max. 10 min or for refueling 5 trains with 200 kg in max. 20 min. In addition, the hydrogen is to be produced on site with a connected load of 2.5 MW. Moreover, sufficient hydrogen is to be stored to ensure refueling for another two days in case of failure or maintenance of the plant.

To produce the required hydrogen, only two different types of **electrolyzers** were considered i.e., alkaline electrolysis (AEL) or proton exchange membrane electrolysis (PEM). Due to the small scale of this project the investment cost for both types of electrolysis were roughly the same. But the operating cost was lower for PEM, hence a PEM electrolyzer was chosen which is offered as an all-in-one solution. Such a solution includes water treatment and hydrogen purification for the electrolyzer which is economically more favorable than designing a separate purification process for the hydrogen produced. The selected electrolyzer produces **1.062 t of hydrogen per day** in continuous operation.

A **storage system** was developed for storing the produced hydrogen. The optimal pressure levels were determined, and a minimum filling pressure was determined that is needed for a correct refueling process. In addition, the pressure in the storage tank must exceed the desired final pressure in the vehicle tank for the overflow refueling process to work. Hence, hydrogen was stored at two different pressures. The **medium-pressure** storage tank operates between 200 bar and 350 bar and the **high-pressure** storage tank operates between 400 bar and 700 bar. The decision of the pressure levels was mainly based on saving space due to significantly smaller tank volumes. This resulted in a total tank volume of **340 m^3** for the medium-pressure storage tank and **40 m^3** for the high-pressure storage tank.

To **transfer** the hydrogen from the electrolyzer to the heavy-duty vehicles across two pressure levels, it must be compressed to the corresponding pressure levels. For this purpose, hydraulically operated, dry-running **two-phase piston compressors** were chosen. Since the electrolyzer is also operated continuously, the compressors also work continuously, thus achieving a constant mass flow. The hydrogen leaves the purification process after electrolysis at a pressure of approx. 30 bar and is stored in the medium-pressure storage tank at 350 bar. The compressor was optimized for a pressure ratio of 3.42 per compression stage and achieves a **mass flow rate of 45 kg h^{-1}** when continuously filling the medium-pressure storage tank with the hydrogen produced by the electrolyser. This results in an almost identical temperature at both pressure levels and minimizes energy loss through heat. At a temperature of 20 °C, the compression requires an output of 86 kW and a heat dissipation of 64 kW. To compress the hydrogen at 20 °C from 350 bar in the medium-pressure storage tank to 700 bar for the high-pressure storage tank, two compressors operate in a parallel manner. Each compressor has a mass flow rate of 80 kg h^{-1} and requires about 45 kW of electrical power at a pressure ratio of 1.41 per stage with a consequent heat flow of 30 kW. The hydrogen is cooled to 20 °C after each compression stage by a heat exchanger and a suitable cooling medium. The redundant design ensures that the second tank can be filled even if one compressor fails. When filling the high-pressure tank from the medium-pressure tank, a **mass flow rate of 156 kg h^{-1}** is achieved by the two compressors used, which enables rapid refilling and thus allows the continuous refueling of heavy-duty vehicles from the high-pressure tank.

The **refueling process** utilizes the overflow method, whereby no further compressor is required between the high-pressure tank and the dispenser for the hydrogen transport. Hydrogen flows from the high-pressure storage tank into the vehicle tank due to the pressure gradient. The refueling of the heavy-duty vehicles was carried out according to **SAE J2601 standards**, which requires cooling before refueling. Data from various dispenser manufacturers indicated a maximum mass flow of 216 kg h^{-1} for busses when cooling to -20 °C. For trains, the maximum mass flow is given as 430 kg h^{-1}, which means that the requested **refueling time** of 20 min must be extended **28 min** when refueling with 200 kg of hydrogen. To comply with the maximum refueling time of trains of 20 min for 200 kg of hydrogen, a procedure could be developed in which a train is refueled with two dispensers simultaneously; here, cooling to -40 °C was assumed for safety reasons.

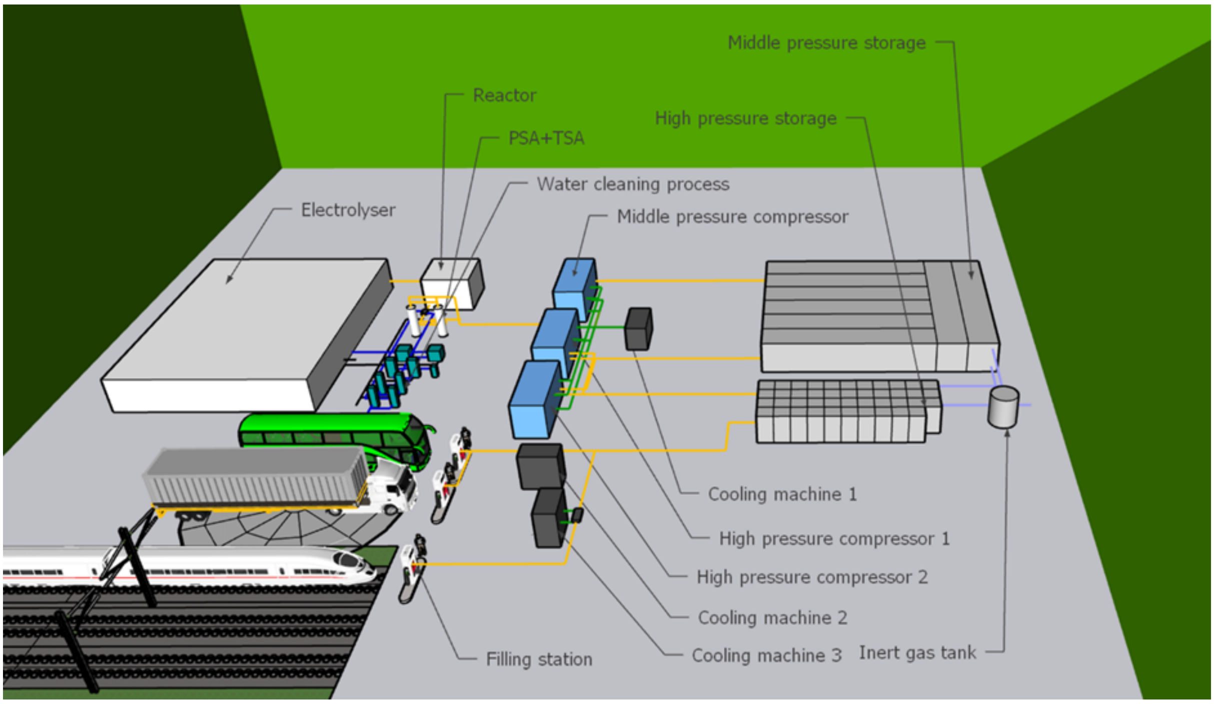
Process and cooling water are obtained from the drinking water network. The process water must be deionized to be used in the electrolyzer. This is not necessary for cooling water. 0.8 – 3.2 m^3 h^{-1} are taken from the main water line and first passed through a coarse particle filter. Particles and sludge are removed here. Part of the water flow (0.4 m^3 h^{-1}) is used to cool the condenser in the hydrogen purification unit and is returned for further purification. In the next step, chlorine is filtered out of the stream using an activated carbon filter. After adding an antiscalant that protects the downstream membranes from incrustations and deposits, salts can be removed in the reverse osmosis unit. The process water is thus purified and can be used in the electrolyzer.

About 30 Nm^3 h^{-1} of **compressed air** is needed to operate the pneumatic valves. To ensure its purity, the compressed air is purified in a system consisting of a particle filter, absorption dryer and refrigeration dryer. All components are connected to an oil separator, which ensures clean separation of oil and aqueous residue. **Nitrogen** is purchased in gas cylinders for economic reasons. It is needed to inert the plant components before starting operation or for maintenance work.

The piping network consists of different materials adapted to the material to be conveyed. Since hydrogen leads to the embrittlement of low-quality pipe materials, high-alloy austenitic stainless steel with a high nickel content (> 8%), designated DIN 1.4404 / X2CrNiMo17-12-2, is used here. For non-critical streams, such as process water, PVC pipes were used due to their lower cost. For the thermal oil, a lower-quality stainless steel DIN 1.403 / X5CrNi18-10 was chosen.

The parameters volume flow, density and flow velocity are important for **dimensioning the pipelines**. From these, the wall thickness is calculated via nominal pressure and nominal diameter according to DIN 10253-2. The pipelines for the hydrogen filling station were designed according to DIN 2401 and DIN 2402. Pressure losses and shocks were classified as negligible after the calculation. To avoid heat and cold losses from the flows, suitable insulation must be selected for the pipes. Streams with temperatures below 0 °C are best insulated with synthetic insulation such as PU foam. For streams with temperatures above 40 °C, mineral insulation like mineral wool is recommended.

The following figure shows a proposed **site plan** that considers the recommended minimum distances between the plant components and thus enables a comprehensive representation of the entire hydrogen filling station. This model can be used to estimate the required number and length of pipelines.



The **energy efficiency** of the overall process is 56.5% (power-to-power). The process requires 3.1 MW to generate 1062 kg of hydrogen which translates to a usable energy stream of 1.75 MW (calculated using the higher heating value). Losses leave the system mainly as waste heat in the electrolyzer, the compressors and in mechanical form. Heat integration is neither reasonable in the electrolyzer, nor in the condenser of the hydrogen purification unit as investment costs exceed savings during operation. These are the only plant components that need heating.

A total amount of nine **heat exchangers** is installed in the plant. The three compressors with two stages each where the hydrogen needs to be cooled down to 20 °C after each stage demand for six of them. One more is needed at the condenser in the hydrogen purification unit. The last two are required before the dispensers, one for bus refueling (-20 °C) and one for trains (-40 °C). For hydrogen pressures below 500 bar, double-tube heat exchangers are the preferred design. Above 500 bar, K°Bond heat exchangers that allow pressures up to 1050 bar and are resistant to hydrogen leakage due to the diffusion bonded design are recommended.

A water-glycol mixture as the **heat transfer fluid** for the compressors seems suitable. In front of the dispensers, the required temperatures can be reached with two chillers, which use thermal oil as heat exchange fluid. For cooling the condenser no chiller is needed.

To safeguard the operations at the station, **fault scenarios** were developed in the sub-processes, followed up by the identification of the control and disturbance variables, and the design of concrete control circuits. Subsequently, the individual control elements were used to design the higher-level communication between the sub-processes. The definition of the circuit sequences for start-up and shutdown, a general blackout concept involving the positioning of the valves and measures for simple maintenance were also designed. A vast majority of the automated system was based on the **functional safety** under the *VDI/VDE 2180* standard. This includes the inspection of potential sources of danger, failure rates of the process technology and counter measuring for the least failure rate.

Inherently the safety requirements are to be adhered to the **safety regulations** and requires working with the local laws and authority in the acquisition of approved permits. One such safety standard is the *TRBS 3151* (an adapted version is being reviewed) which provides comprehensive information on the general requirements for the station including **explosion and fire protection**. The following standards *TRGS 722*, *TRGS 723* and *TRGS 725* also give more detailed information on fire and explosion protection, with *TRBS 2141* on the technical tightness and **safety with steam and pressure**. Regarding the **noise protection**, *TA Lärm* would be used as a reference, as this technical guideline covers the noise emission limits from various sources, shows measurement methods, describes how to assess the noise levels, and offers strategies for noise reduction. Measures that might be implemented with accordance of the latter include sound insulation for buildings near noisy streets or industrial areas, restrictions on the use of loud equipment during certain times of the day and noise barriers along highways or railways.

As for **emission control**, before achieving an initial approval subjected to the Federal Emission Control Act (*BImSchG*) for the construction of the station with an on-site electrolyzer and storage tanks (< 30 t), the location was selected to be in an industrial area. The location of the station was decided on according to the infrastructure market and property conditions, the permits required, and the supply and waste disposal. The first step in applying under *BImSchG* is the submission of the required documents, which could take up to a year. Within two months of submission, the documents are then reviewed of its accuracy and completeness. Finally, a public announcement takes place, where objections are collected and discussion with the applicant followed, resulting to a decision on the approval of the application.

In keeping with the project tasks and timeline, a standard project management plan using **breakdown structures** were employed. The hierarchical representations of a projects component be it the product (PBS), work (WBS), resource (RBS) and cost (CBS) aids in organizing and managing the project, with the key principle MECE at the forefront of planning; mutually exclusive (ME) and collectively exhaustive (CE). The product and work breakdown structures are to be planned out simultaneously i.e., listing the equipment, apparatus, and miscellaneous products, and starting from the planning phase, followed with the construction phase, and ending with handing over to the operator. The resource breakdown structure thoroughly categorizes the human resources and manpower required, construction tools and equipment, logistics, permits & approval acquisition etc. To end, the cost breakdown structure lists all costs from the planning, construction, equipment, and operation of the hydrogen refueling station. Although the PBS, WBS and RBS typically follows a top to bottom approach, the CBS is processed from bottom up.

The total costs were calculated by the summation of the **capital expenses (CapEx)** and the **operation expenses (OpEx)**. The capital expenses are the costs of initial investment in the plant and there are various methods with varying accuracies to calculate the CapEx, whereby for this project a method with -30%/+40% accuracy was chosen. The methods are models by Lang and Hand, which were also used to calculate the cost of hydrogen produced in € kg^{-1}. The **total capital expenses** amount to **€ 25.3 Mio** comprising of medium- and high-pressure storage (30.4% & 20.4%), electrolyzer unit (15.8%), compressors (13%), estate (8%), automation (7.9%), cooling unit (1.8%), pipes (1%), dispenser (0.6%), authorization (0.6%), heat exchangers (0.4%) and utilities (0.1%). Most expensive capital expense were the storage tanks with the medium-pressure storage at € 7.7 Mio and the high-pressure storage at € 5.2 Mio. The electrolyzer unit being the second most expensive at € 4.0 Mio and least expensive was the utilities at € 32,500.

Besides, the results from the **operational expenses** amounted to a total of **€ 4.6 Mio** with a yearly energy consumption of 26 GWh. The highest OpEx to the least are as follows: electrical energy (88.9%), maintenance (8.1%), insurance (2.7%) and water (0.3%). The yearly electrical energy alone costed € 4.1 Mio with 7 ct kWh^{-1} considered and thereby resulted in the cost of hydrogen produced at 9.1 € kg^{-1}. Two additional scenarios were calculated with electricity prices at 16 ct kWh^{-1} resulting in total OpEx of € 6.6 Mio per year and 15.97 € kg^{-1} H_2, and at 12 ct kWh^{-1} with a total OpEx of € 5.5 Mio per year and 13.23 € kg^{-1} H_2. Additionally, the **amortization** was calculated, but only with one model of the electricity price at 7 ct kWh^{-1}. The probed three different time periods for the amortization, its respective cost of hydrogen produced, and turnover are as follows: (5 years, 22.06 € kg^{-1} H_2, € 9.1 Mio); (10 years, 15.93 € kg^{-1} H_2, € 6.6 Mio); (15 years, 13.89 € kg^{-1} H_2, € 5.8 Mio).

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Partner project with Covalion, a trademark of Framatome

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