Integrated Hydrogen Infrastructure Design and Optimization: A Case Study at Graz University of Technology Centre Hydrogen Research

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Abstract: Due to increasing hydrogen demands resulting from highly sophisticated R&D projects at the Graz University of Technology Centre Hydrogen Research, it is planned to supply the respective institutes by a new hydrogen pipeline connected to a new onsite electrolysis test field in the MW scale. The pipeline will be fed and interconnected to the new electrolysis test field located near the existing central hydrogen infrastructure hub at HyCentA and LEC/ITnA. Existing hydrogen compressor- and storage infrastructure as well as an existing natural gas compressor, which was converted to pure hydrogen operation, will be integrated. The interconnection and design options of the new systems that will be combined to a complex central hydrogen infrastructure hub are being examined based on the volatile hydrogen demand of the institutes at Graz University of Technology. The volatile hydrogen demands of all consumers are analysed using a statistical approach to develop representative annual hydrogen consumption profiles. These profiles are used as input to define the overall plant configuration, which is optimized in simulation studies by varying relevant plant parameters (e.g. hydrogen production capacity or storage capacity and storage pressure level). Furthermore, space restrictions, regulatory approval capability of the facility, economical and safety aspects were considered to find the optimal infrastructure configuration that meet all technical, economical and legal requirements.

Keywords: hydrogen infrastructure, electrolysis system, volatile hydrogen demands, statistical evaluation, hydrogen infrastructure optimization, investment comparison analysis

1 Introduction and Objectives

Given the pressing challenges created by climate change, the necessity to transition energy systems becomes evident. Central to this transition is the application of cleaner and sustainable technologies, designed to minimize the environmental impact. For that transition hydrogen technologies play a central role because of their capacity to serve as a sustainable energy carrier, encouraging decarbonization, enhancing energy storage capabilities and enabling the integration of renewable sources. [1]

Research activities in the field of Hydrogen Technologies at the Graz University of Technology has led to the implementation of highly sophisticated R&D H_2-research infrastructure at several institutes. Besides H_2-(Co-) fired industrial scale gas burner (1.5 MW), hydrogen fuelled Internal Combustion Engines for mobile applications, industrial and maritime applications of up to 3.5 MW, gas turbine combustion chambers, Fuel Cell Testing Infrastructure for Single Cell-, Stack- and System Testing with a nominal power output of up to 160 kW have been implemented and will be extended step by step. Furthermore R&D Infrastructure for Electrolysis Testing from cell to small scale system level is in operation. These industry-oriented applications at different institutions at Graz University of Technology within the hydrogen field serve as the foundational framework for the establishment of new hydrogen R&D-infrastructure at the same site. Therefore, test capabilities with an electrolysis test field for system testing at industrial scale (MW-level) will be implemented. The named applications result in complex and volatile demands for hydrogen, providing potential for research to interconnect hydrogen consumers and producers at Graz University of Technology. Existing infrastructure with different storage, compression, distribution and gas analysis capabilities serves as nucleus for an interconnected intelligent laboratory for industrial scale hydrogen testing. A natural gas compressor has being refitted to hydrogen operation meeting highest hydrogen purity demands defined by international standards for PEM-Fuel Cell applications, see [2,3].

Combination of R&D applications at the campus result in a complex and volatile demand for hydrogen. Different pressure levels, mass-flows and hydrogen quantities have to be met. Required testing pressure levels varying from 1 bar up to > 700 bar, mass flows from 0.1 kg/h up to 150 kg/h and testing durations from 1 hour up to 24/7 testing hours.

Optimization and design objective for a new interconnecting hydrogen infrastructure is to maximize hydrogen demand coverage by intelligent management of production, storage, distribution, consumption modules with a forecasting logistic-concept.

2 Method for optimizing complex hydrogen infrastructure configurations

The development of an optimised hydrogen infrastructure requires the consideration of technical, economic, legal and safety aspects. These multilevel and at each level multiparameter optimisation task requires several iteration loops on technical, economic, legal and safety level. The flow chart illustrated in Figure 1 can be used as basic guideline for an efficient workflow. The sequence of most important process steps from the conceptual phase to the optimized hydrogen infrastructure configuration is depicted. Various interconnected iteration loops are necessary in order to obtain the techno-economic optimized infrastructure

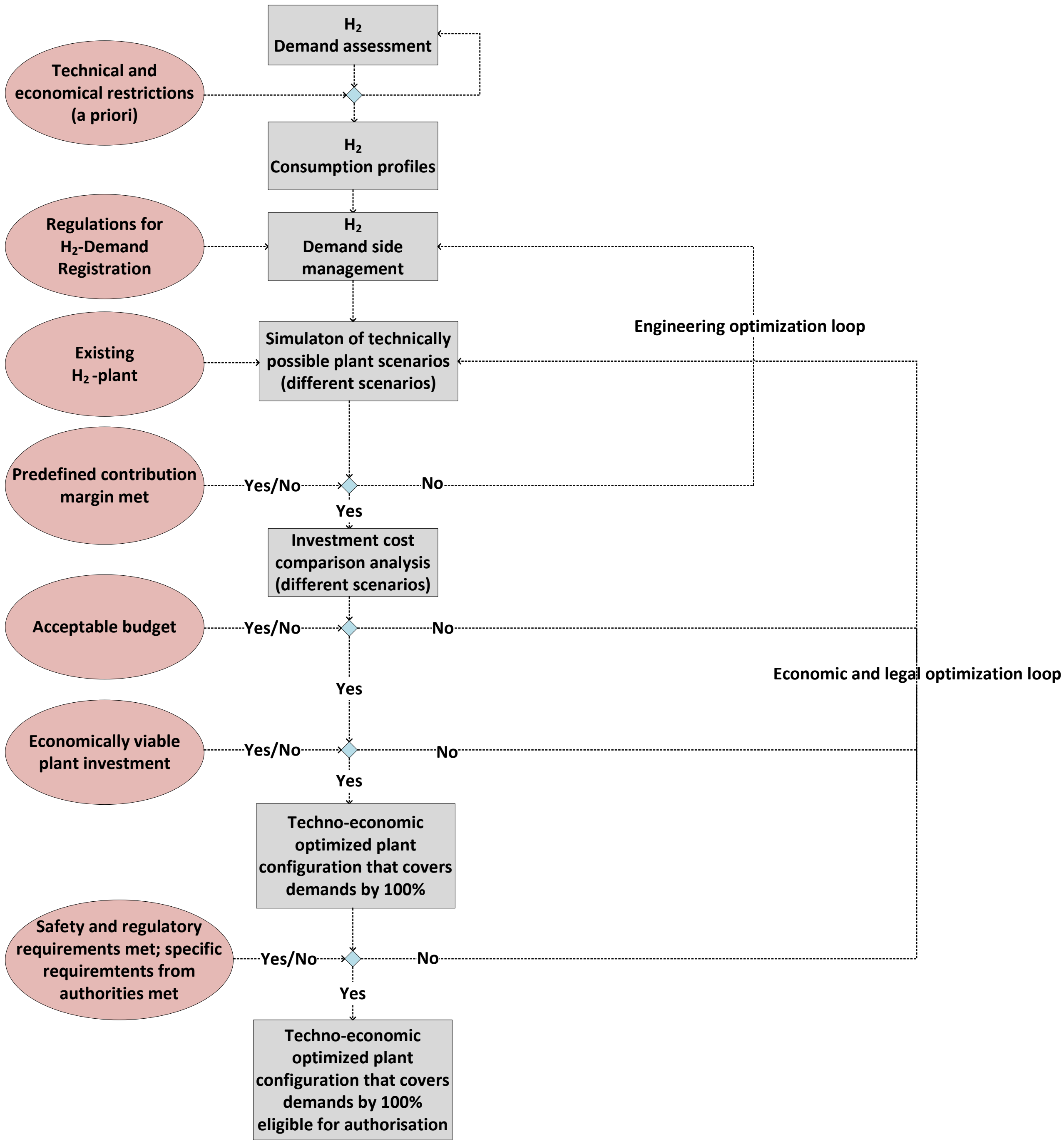


Figure 1: Flow chart of process steps from preliminary infrastructure design to the optimized hydrogen plant configuration

2.1 Generation of hydrogen consumption profiles

Through the survey of the volatile demands of the institutes at TU Graz, an analysis of the necessary hydrogen demand has been conducted. The identification of the required test benches and their specifications enable effective support for research activities and ensures that the hydrogen infrastructure to be developed meets the hydrogen demands of each institute. In this process, the demands were systematically categorized into the required pressure levels, flow rates, and test benches. Careful consideration was given to the hydrogen infrastructure, specifically regarding flow rates in the pipeline and its limitations.

Additional parameters collected for the survey are as follows: duration per experimental day in hours, continuous duration of the demands in hours, and experimental days per month. From these, the sum of kg/month was calculated along with the number of days per year of each demand. To provide a realistic representation of the demands, a frequency factor was introduced. The definition of the frequency factor, indicates how often the required hydrogen demand defined by the institute can be expected in a year in days. From the demand assessment, 42 different demands resulted for the respective institutes.

In the first step of the demand assessment, an annual hydrogen demand of 108 tons per year was determined. These requirements were then compared to the actual needs of the past three years. Since the actual demands deviated significantly from the 108 tons per year, a revision of the demand assessment was conducted. The results of the revised demand assessment by each institute are shown in Table 1 and Figure 2. The institute C defined a minimum and a maximum demand for low-pressure and for medium-pressure demand and this results in two different annual sums of hydrogen per year that need to be covered (min: 50.3 t/a and max: 70.8 t/a) by the hydrogen infrastructure.

Table 1: Summary of revised hydrogen demands of each institute categorized in three different pressure levels

Institute	**H_2-Demand low-pressure (≤ 80 bar) [kg/a]**	**H_2-Demand medium-pressure (≤ 300 bar) [kg/a]**	**H_2-Demand high-pressure (> 300 bar) [kg/a]**	**Sum of total H_2-Demand [kg/a]**
A	2 655	5 158	1 522	9 335
B	9 590	/	/	9 590
C	**Max: 25 920** **Min: 12 960**	**Max: 14 976** **Min: 7 488**	/	**40 896,** **20 448**
D	3 738	1 068	3204	8 010
E	2 966	/	/	2 966
Max. Sum	**44 869**	**21 202**	**4 725**	**70 797**
Min. Sum	**31 909**	**13 714**	**4 725**	**50 349**

Nevertheless, the mere collection of the 42 demands, does not provide information on whether the collected hydrogen demands are realistic and can be timely met and provides insufficient information for the design of the hydrogen infrastructure. In general, the volatility of the collected demands is challenging to predict.

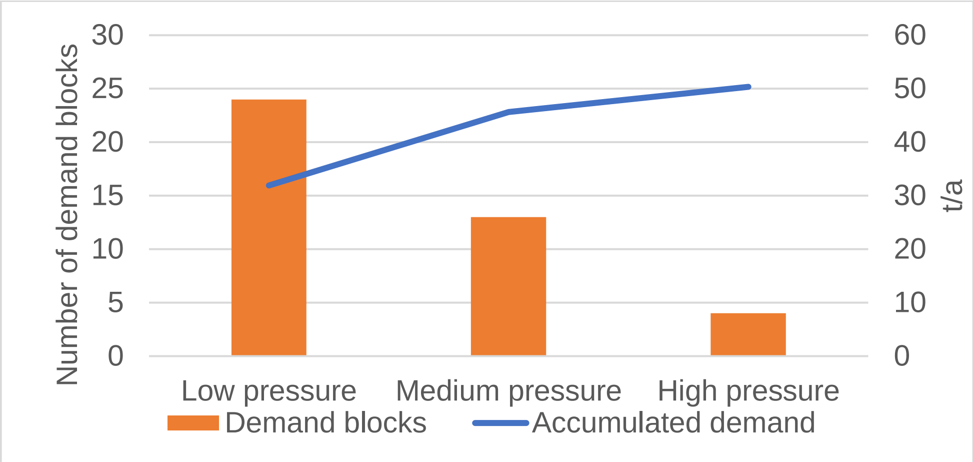


Figure 2: Hydrogen demands over a year categorized in the three pressure levels based on minimum scenario (50.3 t/a)

Therefore, it is necessary to apply a tool that can simulate the volatile occurrence of these demands. To ensure a more realistic distribution and coverage of these demands, a statistical distribution approach for the development of consumption profiles was chosen. The 42 demands are randomly distributed over a year using a MATLAB-based script. Additionally, for the development of this random distribution, further assumptions and boundary conditions were established. These limits were implemented due to the prior execution of a preliminary plant expansion, aligning with the constraints set by the already existing hydrogen infrastructure. This includes the existing high and medium-pressure storage on site, as well as the compressor 1 (final pressure 890 bar) and the compressor 2 capable of compressing low-pressure hydrogen to 600 bar. Other factors that define the limits are the requirements of demands regarding the technologies tested at the institutes. In this context, the major consumers additionally define the specified limits in terms of pressure, flow, and duration.

The major consumers in terms of hydrogen demand are for example large engines up to 3.5 MW leading to hydrogen demand of 150 kg/h at 80 bar and 100 kg/h at medium-pressure at 300 bar, further different engines result in a hydrogen demand of 26.7 kg/h at a high-pressure level of 1 000 bar. Considering all the above-named factors, following limits and boundary conditions for the generation of the consumption profiles have been defined. It is to mention that any demand that does not fall within these boundary conditions will be rejected during the creation of consumption profiles and considered as not covered. In order to not reject any demand an implementation of a demand side management tool is crucial, to ensure that the demand never surpasses the flow rate limits of corresponding pressure levels.

Table 2: List of defined boundary conditions for the generation of consumption profiles

Defined boundary conditions	**Value**
Allocation of the demands to three pressure levels:	
Low pressure demand	≤ 80 bar
Medium pressure demand	≤ 300 bar
High pressure demand	> 300 bar
Maximum flow rates limited to:	
Low pressure flow rate	150 kg/h
Medium pressure flow rate	100 kg/h
High pressure flow rate	26.7 kg/h

Further boundary conditions considered:

- Process each hydrogen demand preferably in a single run (to prevent interruptions of experimental runs)
- Operating hours for hydrogen supply: MON - FRI: 08:00 – 19:00

In order to derive a randomly consumption profile from the collection of demands and the defined boundary conditions, the following steps were executed within the Matlab-based script. In the Matlab-based script demand block objects were created for every specific demand. Each demand block object contains information about the institute and testbench, pressure level, mass flux demand, duration per day, days per month, frequency per year and resulting days per year, as mentioned above. A frequency factor per year was used to set random active months. For a frequency of 0.16667 the two active months were randomly set to October and December for random profile A and to February and September for random profile B and so forth. For the random pressure level load profiles low, medium and high according to the pressure levels defined the indexes of the demand blocks were randomized. Then starting with the first entry in the randomized index vector, the script checks if it can assign the first occurrence of the given block to the corresponding pressure level load profile by checking if it is an active month and if enough mass flux capacity is available in the pipeline. If both results are true, the occurrence is assigned to the profile, the demand block object is set to active, the start time and end time is set. This procedure is continued for each demand block by the random index vector.

Before the assignment procedure of demand blocks for the next timeslot is started. All active demand block objects are checked if the time is equal to the set end time. If true the active entry of the object is set to false, the occurrence entry is increased by one and the available capacity for the given pressure level is increased by the mass flux demand of the now inactive demand block object If the occurrence entry is equal to the days per month entry, the finished entry is set to true and the demand block object will not be activated for the current month. When the month changes, the finished entry is set to false again. Then the assignment procedure of demand blocks for the next timeslot is started, followed by the checking procedure and so forth until the first random load collective is finished at 31.12. 24:00.

Afterwards the random load collective is checked by comparing the sum of the occurrence of every block to the sum of days per year for every block. If more than 0.5 % of the occurrences cannot be assigned, the load profile is rejected and the procedure continues with the next random index vector which was not used before. The generation of consumption profiles is continued until significant amount of randomly distributed profiles are created, where 99.5 % of the occurrences are assigned.

Generated consumption profiles

Under the predefined boundary conditions 20 randomly generated consumption profiles over a year have been generated using the described method. More than one consumption profile was created to represent different sequences of the occurrences of the 42 demands and make a statistical analysis of the performance regarding contribution margin and self-sufficiency for different hydrogen infrastructure scenarios.

Based on historical hydrogen demands and the calculated results the hydrogen demand scenario with 50.3 t/a is applied for the generation of consumption profiles.

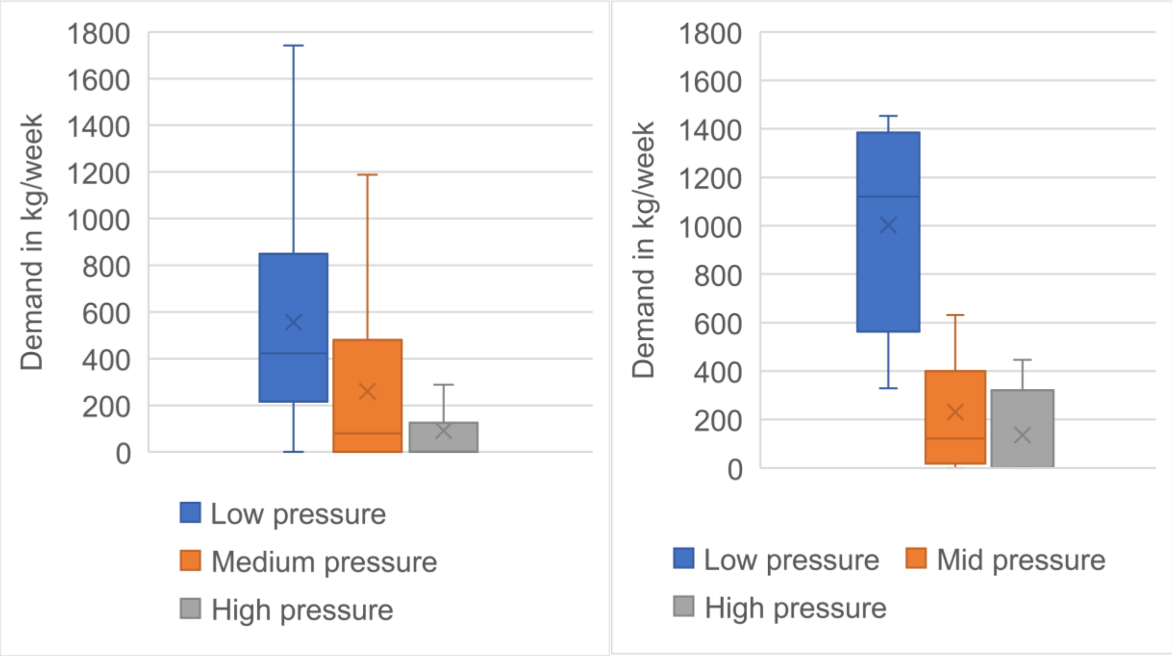


Figure 3: Distribution of the weekly demands across all consumption profiles and the distribution of the 75%-of-the-time or less demands of all consumption profiles in a year

Figure 3 shows on the left the distribution of the demands of the three corresponding pressure levels in kg/week across all 20 randomly generated consumption profiles. The low-pressure demand constitutes the largest proportion of all pressure requirements. This result is incorporated into the preliminary design of the hydrogen infrastructure, as it involves expanding the low-pressure storage to meet the demand. Further the 75 %-of-time demands or less, means that 75% of time, the average weekly demand is this amount or less. Yet again, it shows the high hydrogen demand of low-pressure. The large interquartile range of the 75 %-of-time demands derives from the random assignment of demand blocks, which leads to 75 %-of-time weeks containing almost only low pressure demands or combinations of low, medium and high pressure demands.

The consumption profiles generated by the MATLAB-based script represent a more realistic sequence of the volatile hydrogen demands, originating from the variety of testing sequences at the institutes. The generated consumption profiles serve as a basis for the design of the H_2 infrastructure via a Simulink-based simulation.

2.2 Definition of preliminary hydrogen infrastructure configuration and simulation scenarios

In the simulation model, the hydrogen infrastructure is designed and optimized based on the generated consumption profiles. Given the existing facilities, certain factors are defined in a preliminary design and serve as a starting point for the simulation of the infrastructure design. The following factors are considered for the preliminary design and as boundary conditions for the simulation:

An important factor limiting the preliminary design of the infrastructure for simulation is the space requirement defined by the available area. The available space, does not allow for horizontal gas storage tanks because they would not fit into the available space. Therefore, construction for gas storage must be done vertically. Safety distances regarding fire protection, explosion protection, and escape routes define a certain arrangement possibility in advance.

Furthermore, the existing hydrogen infrastructure with its existing facilities including compressor facilities, storage options in the medium-pressure and high-pressure ranges, shown in Table 3 have an impact on the design beforehand [4]. It is also worth mentioning that temporal processes, such as approved operating times are taken into account in the preliminary design.

Table 3: Parameters of existing infrastructure as boundary conditions for the preliminary design of the expanded hydrogen infrastructure

Existing hydrogen infrastructure		
Medium pressure storage		
	Nominal pressure [bar]	300
	Storage mass [kg]	25
High-pressure storage		
	Nominal pressure [bar]	850
	Storage mass [kg]	22.5
Compressor 1		
	Conveying capacity [kg/h]	2
	Discharge pressure [bar]	950
Compressor 2		
	Conveying capacity [kg/h]	25
	Discharge pressure [bar]	600
Trailer		
	Nominal pressure [bar]	300
	Storage mass [kg]	934

A high amount of low-pressure demand, which will be distributed via the hydrogen pipeline, already suggests in the preliminary design that the hydrogen infrastructure needs to be expanded with a larger low-pressure gas storage in order to cover the demand when needed. The larger low-pressure gas storage serves as a buffer because the electrolysis system, operating at 80 bar output pressure, will not be producing 24/7 due to maintenance, breakdowns, or if the required quality (ISO 14687:2019 [2] is not achieved the hydrogen will be vented into the environment or the electrolysis system is operated within the test program and not within the demand-driven operation. Additionally, the demands are temporally volatile, causing a mismatch between electrolysis system production time and demand time. Furthermore, larger medium-pressure demands indicate that the existing medium-pressure storage system must also be enlarged. The existing hydrogen trailer ensures partial coverage for higher medium-pressure demands and is considered as an additional factor in the preliminary design. The available budget for the expansion is introduced as a factor. Therefore, for example, the expansion and sizing of the low-pressure gas storage is limited by the available budget. A simple pre-calculation of the sums of the demands yields the expected electrolysis system capacity.

In the first simulation study, a 1 MW electrolysis system was assumed for the initial demand of 108 tons hydrogen per year. In this simulation study, the use of a large low-pressure storage

(Scenario 1) or a large medium-pressure gas storage (Scenario 2) was compared and further the combination of both large gas storages (Scenario 3). Details of the considered scenarios are shown in Table 4. The aim was to investigate the contribution margin achieved by the considered configurations. Furthermore, the study explored the source of hydrogen deriving from electrolysis or from trailer.

Table 4: Details of considered scenarios (varying gas storage size) for 1MW-Electrolysis-system including the parameters from the existing infrastructure in Table 3

		Scenario 1	**Scenario 2**	**Scenario 3**
Electrolysis system	Conveying capacity [kg/h]	19	19	19
	Outlet pressure [bar]	80	80	80
Low-pressure storage	Nominal pressure [bar]	80	30	80
	Storage mass [kg]	308	2,44	308
Medium-pressure storage	Nominal pressure [bar]	300	500	500
	Storage mass [kg]	25	557	557
High-pressure storage	Nominal pressure [bar]	950	950	950
	Storage mass [kg]	72	72	72

In the next step, due to the revised hydrogen demand (chosen scenario: 50.3 t/a) a 250 kW electrolysis system was used as the basis for the preliminary design and set in the simulation. Furthermore, the 250 kW electrolysis system was also considered in terms of the budget. For the 250 kW electrolysis system, 8 000 full-load hours for the stationary electrolysis system base load were assumed, allowing for the production of 26 tons of hydrogen per year. The amount of hydrogen produced and full-load hours will likely be different caused by the impact of the chosen infrastructure configuration, operation strategy, the consumption profiles and trailer logistics. The remaining hydrogen demand is covered though trail supply. The number of trailer and the general operating strategy of the hydrogen infrastructure (storage management and regeneration, hydrogen distribution in relation to demand) are optimized in the simulation model. Three stationary tank sizes were compared, and their impact on the contribution margin of different pressure levels was examined. It was investigated whether and what influence the doubling of the 48m^3 storage (Scenario 4) to 96m^3 (Scenario 5) has on contribution margin and further what impact the deployment of a 250 bar-storage, 53m^3 (Scenario 6) could have on the contribution margin.

Further details regarding the parameters used for the simulation scenarios are shown in Table 5.

Table 5: Parameters for simulated scenarios (comparison of low-pressure storage sizes) system including the parameters from the existing infrastructure in Table 3

		Scenario 4	**Scenario 5**	**Scenario 6**
Electrolysis system	Conveying capacity [kg/h]	3.15	3.15	3.15
Low-pressure gas storage	Nominal pressure [bar]	80	80	30
	Storage mass [kg]	308	616	2.44
	Volume [m^3]	48	96	1
Medium-pressure gas storage	Nominal pressure [bar]	300	300	250
	Storage mass [kg]	25	25	557
High-pressure gas storage	Nominal pressure [bar]	950	950	950
	Storage mass [kg]	72	72	72

The 20 annual demand profiles have been loaded into the simulation model as consumption profiles, and various runs were simulated using the initially designed hydrogen infrastructure. The contribution margins of different pressure levels (low pressure, medium pressure, and high pressure) were compared for the applied gas storage sizes. Furthermore, an investigation was carried out on how the demand is precisely met, specifically, how much hydrogen can be covered by electrolysis system and the proportion of demand coverage attributed to the hydrogen trailer.

For the three scenarios of the 250 kW electrolysis system, an additional scenario was examined. It was considered at which state of charge (SOC) the trailer leaves the site for a defined number of trailers per week. In this scenario, boundaries for trailer logistics were defined as follows: trailers arrive six times a week at 08:00 with a 100 % state of charge (SOC). By investigating the remaining SOCs, it can be estimated how many trailers would be required in a year.

2.3 Electrolysis system operating strategy

The operating strategy of the electrolysis system is impacting the efficiency of the demand coverage as well as the design of the hydrogen infrastructure. The operating strategies for electrolysis systems vary based on the specific application, energy source availability, and system requirements. Some common operational strategies for electrolysis system include:

Continuous operation where the electrolysis system operates at a steady state, the demand-driven operation where the adjustment of the production rate is directly influenced by the demand, the load-following operation, where the electrolysis system adjusts its operation in real-time to match variations in electricity supply, the peak shaving operation where the electrolysis system operates during periods of low electricity demand and shuts down during peak demand (cost reduction), the grid balancing operation, where the electrolysis system contributes to grid balancing by absorbing excess electricity during periods of oversupply and providing additional capacity during peak demand enhancing grid stability. In the context of the volatile demand situation at TU Graz, it becomes evident that the demand-driven electrolysis system operating mode is the operational strategy that can ensure the coverage of hydrogen needs and is implemented in the simulation of the design of the hydrogen infrastructure. Despite this, various electrolysis systems will be operated under test program guidance at the electrolysis system test field, potentially creating an additional time factor between demand and production. However, for the simulation, the demand-driven operating strategy was considered.

Operating strategy for the electrolysis system in the simulation studies:

Figure 4 shows the schematic of the preliminary designed hydrogen infrastructure and the operating strategy as flow chart, which are implemented in the HYDRA simulation model. HYDRA is an MatLab Simulink library developed by HyCentA containing various elements of hydrogen infrastructure and has been used for techno-economic analyses ranging from hydrogen production and storage as well as hydrogen refuelling stations. A recent publication based on HYDRA techno-economic analysis discusses guidelines for sizing regional electrolysis systems [5].

The elements and the operating strategy shall be discussed now by following example. Hydrogen production starts when the state of charge of either the low-, medium- or high-pressure storages falls below 90%. The operating point of the electrolysis system is adapted depending on the path. Where the path to low-pressure storage imposes no limitations and the path to the medium-pressure storage is limited by the capacity of compressor 2. For the path to the high-pressure storage the imposed limitation on hydrogen production depends on the capacity of compressor 1 or compressor 2 depending on the current pressure level of the high-pressure storage. The supply by trailer is activated when either the low pressure or medium-pressure demand signal is higher than the hydrogen mass flux supplied by the low- or medium-pressure storage. At each node, after compressor 2 and after the medium pressure storage system the hydrogen mass flow can be split and directed. Where the top priority is to regenerate the high-pressure storages, then the medium-pressure storages and then the low-pressure storages as depicted in Figure 4. The SOC of the high-pressure storage system drops below 90 %. The electrolysis system is switched on and begins hydrogen production at nominal power. The produced hydrogen is directed towards compressor 2. Compressor 2 compresses the hydrogen mass flux, if the hydrogen mass flux is larger than the compressor capacity at corresponding suction pressure an overload signal is sent to the electrolysis system, which decreases its operating point accordingly. The compressed hydrogen after compressor 2 is directed towards the high-pressure storage system. If the pressure level in the high-pressure storage system is less than the pressure level after compressor 2, the hydrogen is fed directly into the high-pressure storage system. If the pressure level of the high-pressure storage system is larger than or equal to the pressure level after compressor 2, the compressor 1 is activated and compresses the incoming hydrogen mass flow. This compressor also sends an overload signal if it cannot process the incoming mass flux to the electrolysis system, which than changes its operating point to change hydrogen production accordingly. Hydrogen production is stopped as soon as the high-pressure storage system reaches 100 % SOC. If the low-pressure and/or the medium pressure storage systems SOCs fall below 90 % the operating point of the electrolysis system is reset to nominal power.

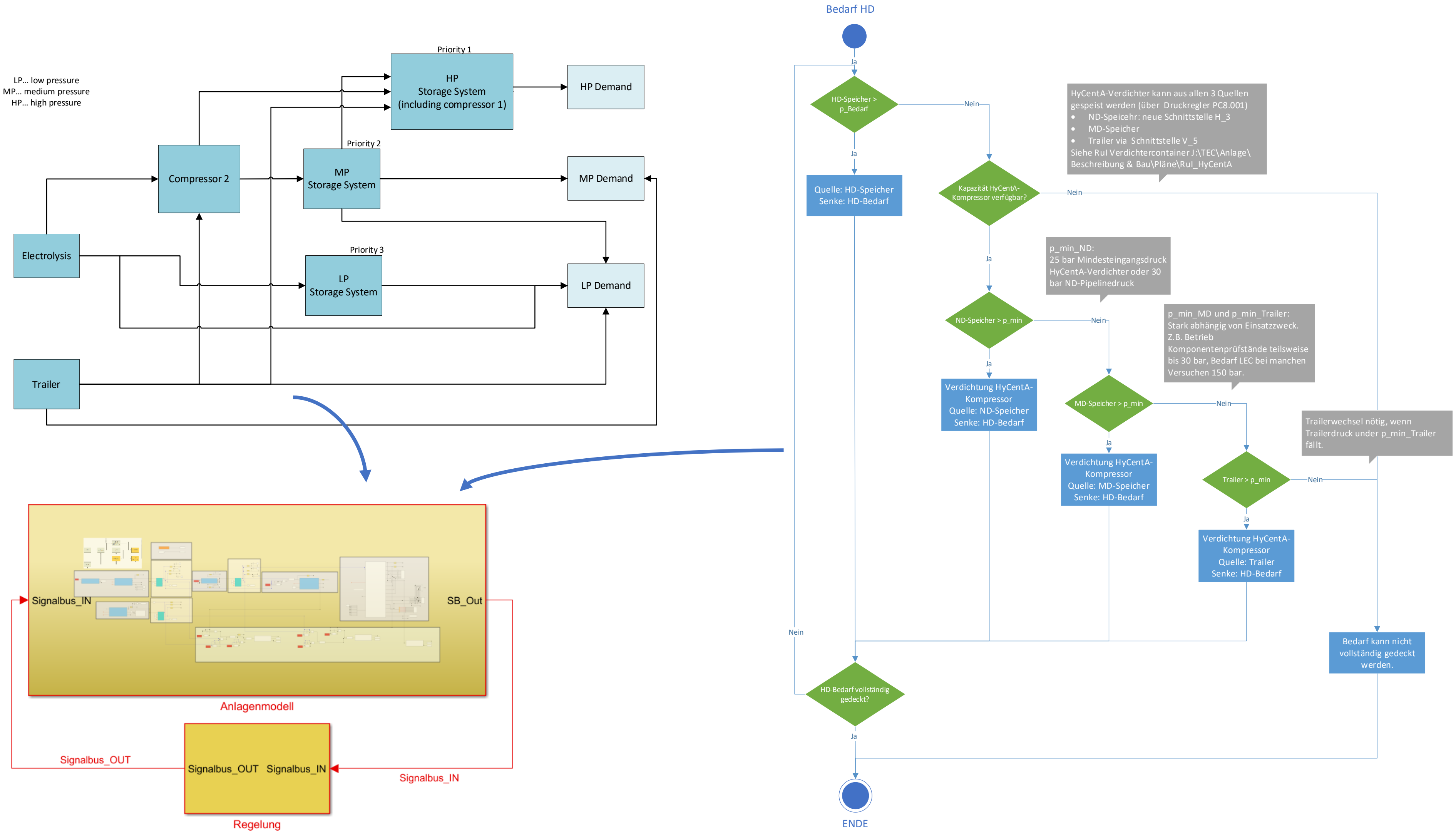


Figure 4: Schematic representation of the preliminary designed hydrogen infrastructure including the consumers for low, medium and high pressure demands on the top left. The operating strategy of the system as a flow chart is shown on the right side. The plant configuration and the operating strategy are combined in the simulation model used for analysing the performed simulation scenarios

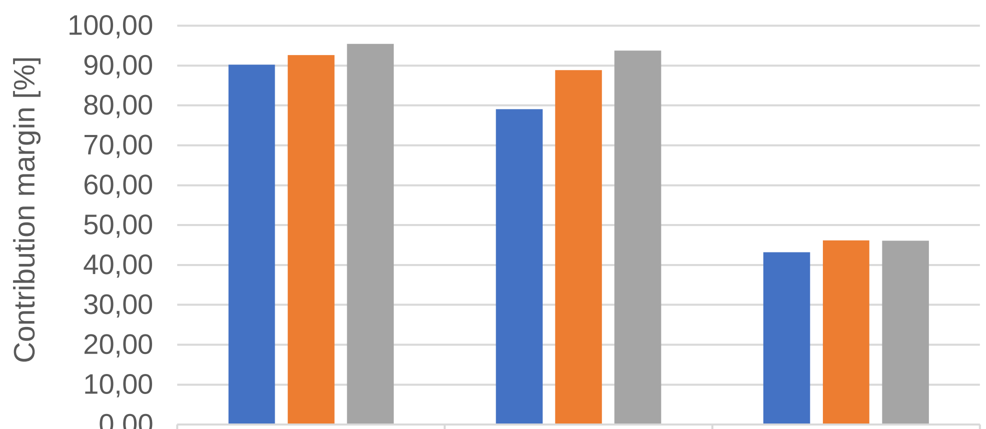
3 Results of simulation studies

In this chapter the results of the performed simulation studies for the 1 MW electrolysis system and the 250 kW electrolysis system are discussed.

3.1 Results of 1 MW electrolysis system scenarios

In the performed simulation studies for the 1 MW electrolysis system three different scenarios have been investigated. Scenario 1 considered a large low-pressure storage. Scenario 2 considered a large medium-pressure storage and Scenario 3 considered the combination of a large low-pressure storage and a large medium-pressure storage.

In Figure 5 the contribution margins of the three considered scenarios are shown. Scenario 3 (combination of large low-pressure storage and large medium-pressure storage) reaches the highest contribution margin for low-pressure and medium-pressure level. The combination of a larger low-pressure storage and medium-pressure storage ensures a higher coverage of the restrictive pressure levels. The contribution margin for the high-pressure level is not significantly impacted by the combination in comparison to the Scenario 2 where only a larger medium-pressure storage is considered. The lower contribution margin for the high-pressure demand can be explained. The highest possible high-pressure demand that can be covered by the considered system is 12.7 kg/h at 700 bar and one high-pressure demand exceeds this limitation, leading to a lower contribution margin overall.

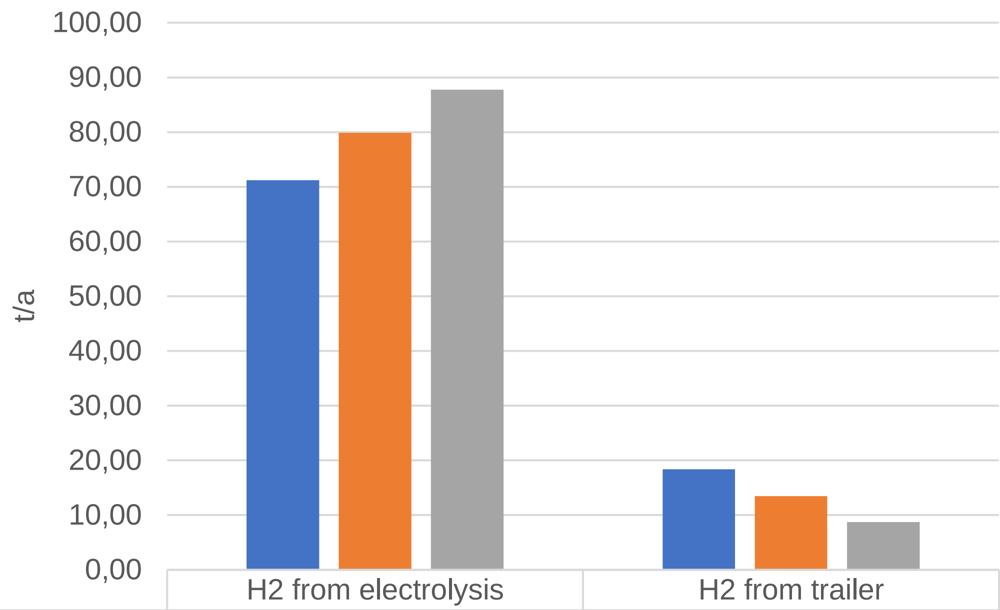


	Contribution margin LP	Contribution margin MP	Contribution margin HP
Scenario 1	90,23	79,06	43,22
Scenario 2	92,67	88,87	46,17
Scenario 3	95,46	93,72	46,05

Pressure levels of H2 demand
LP....low pressure ≤ 80 bar; MP...medium pressure ≤ 300 bar; HP...high pressure > 300 bar

Figure 5: Contribution margins of all three scenarios for the 1 MW electrolysis system simulation study

Figure 6 shows the origin of the hydrogen in a year for the 108 t/a demand either from 1 MW-electrolysis system or supplied by the 300 bar trailer. In general, the 1 MW electrolysis system is the main source for all three scenarios compared to the trailer. Looking at the scenarios, the scenario 3 (large low-pressure and large medium-pressure storage) reaches the highest supply by the electrolysis system, due to its higher storage capacity.

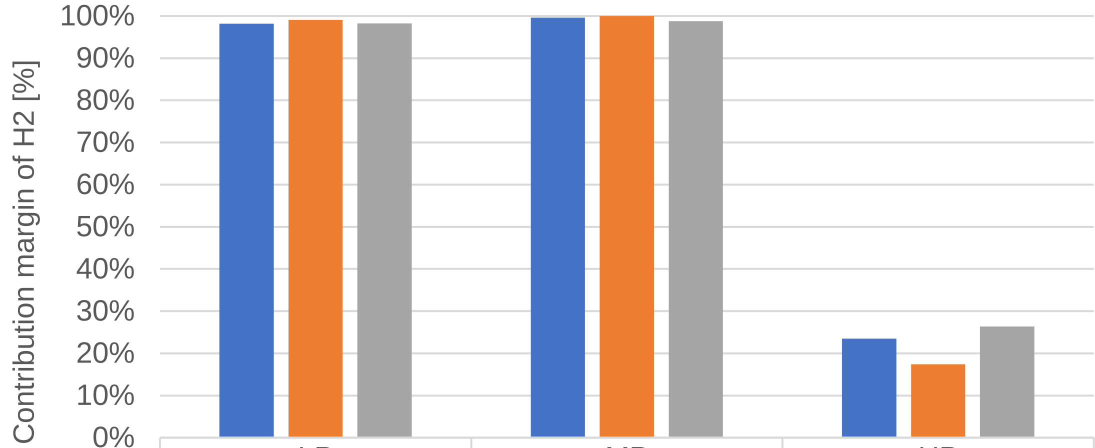


	H2 from electrolysis	H2 from trailer
Scenario 1	71,21	18,38
Scenario 2	79,87	13,48
Scenario 3	87,75	8,73

Figure 6: Hydrogen sources (electrolysis system or trailer) for all three scenarios for 1 MW electrolysis system

3.2 Results of 250 kW electrolysis scenarios

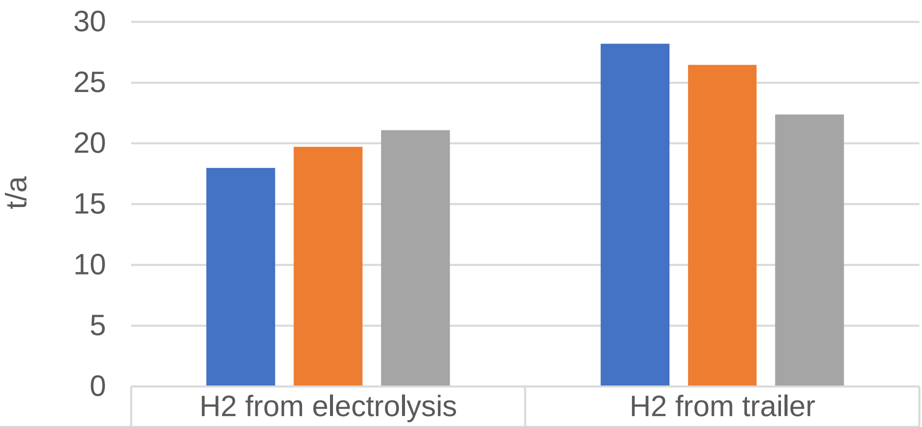
In the performed simulation studies for the 250 kW electrolysis system three different scenarios have been investigated. Scenario 4 considered a 48 m^3-low pressure storage. Scenario 5 considered a 96 m^3 low-pressure storage and Scenario 6 considered a 53 m^3 medium-pressure storage.



	LP	MP	HP
Scenario 4	98,20%	99,60%	23,50%
Scenario 5	99,10%	100,00%	17,40%
Scenario 6	98,28%	98,81%	26,38%

Figure 7: Contribution margins of all three scenarios for the 250 kW electrolysis system simulation

The contribution margins of the examined scenarios for the 250 kW electrolysis system are illustrated in Figure 7. The contribution margin for the low-pressure demand and the medium-pressure demand of the scenario 4 does not differ significantly from the scenario 5. Both scenarios (4 and 5) reach a high contribution margin for the low-pressure demand and medium-pressure demand directly through electrolysis system or the trailer. The gas storage with 53 m³ and 250 bar from the scenario 6 performs slightly worse in terms of low-pressure demands and medium-pressure demands. The key factor is that the storage from the scenario 6 always requires compressor 2 and cannot be directly fille by the electrolysis system or trailer, thereby minimizing the coverage of the demand. The lower contribution margin for the high-pressure demand can be explained. The highest possible high-pressure demand that can be covered by the considered system is 12.7 kg/h at 700 bar and one high-pressure demand exceeds this limitation, leading to a lower contribution margin overall. The introduction of a demand management would help allocate a longer time slot for the regeneration of the high-pressure storage, allowing the registered demand, for example in terms of mass, to be delivered over an extended duration. On the other hand, for a specific demand, the high-pressure storage would need to be expanded to deliver the exactly 26.7 kg/h at 1000 bar.



	H2 from electrolysis	H2 from trailer
Scenario 4	17,97	28,19
Scenario 5	19,72	26,45
Scenario 6	21,09	22,37

Figure 8: Hydrogen sources from electrolysis system or trailer for 250 kW electrolysis system based scenarios

In Figure 8, the source of hydrogen for the three considered scenarios, coming from electrolysis system or from the trailer is shown. Compared to the results for the 1-MW electrolysis system and a yearly demand of 108 t/a shown in Figure 6, these results here differ significantly. The 1 MW-electrolysis system could cover the 108 t/a on its own not even working full load hours. In this case, the 250 kW-electrolysis system would only cover the half of the 50.3 t/a demand on its own. Due to the operating strategy implemented in the simulation and the volatile demands, even more hydrogen has to be supplied by the trailer for scenario 4 and scenario 5.

Figure 9 shows the SOC of the all trailers when leaving the site for the considered scenarios of the 250 kW electrolysis system. In general, it can be stated that for 250 trailers, the state of charge (SOC) at the end of the day is greater than or equal to 90 %. For 36 trailers, the SOC at the end of the day is less than 75 %. For 13 trailers, the SOC at the end of the day is less than 50 %. The lowest SOC rate for the trailer results from the scenario 1 with the site 48 m^3-storage (80bar) and the highest SOC rate for the trailer results from the scenario 3 with the site 53 m^3-storage (250 bar).

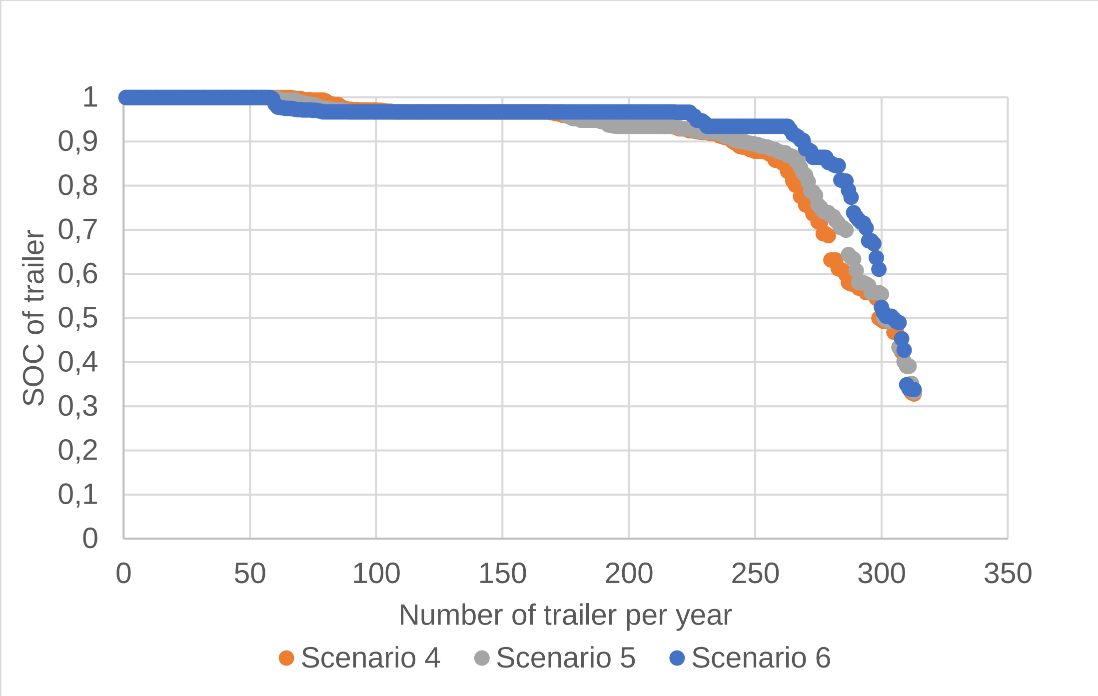


Figure 9: Sub-scenario of 250kW electrolysis system investigating the SOC of trailer when leaving the site

The 48 m^3-storage is directly filled via the trailer whereas the 53 m^3-storage additionally requires the compressor 2 in order to be filled, leaving less time for the trailer to reduce its SOC before the next trailer arrives. Additionally, the electrolysis system produces more hydrogen in Scenario 3 (52 m^3-storage) compared to Scenario 1 (48 m^3 storage) (shown in Figure 8) leaving resulting in a higher remaining SOC for the Scenario 3. The reason for the higher state of charge (SOC) of the trailer with the 96 m^3 storage compared to the 48 m^3 storage is that more hydrogen is produced by electrolysis system and stored in scenario 6 (96 m^3 storage) as shown in Figure 8. The results of the simulation studies indicate that the 48 m^3 low-pressure storage tank is a suitable storage size to meet the low and medium-pressure demand, which constitute the majority of the needs. The choice of electrolysis system size is determined as 1 MW, as it could meet the demand and operate efficiently within the test-driven program, where the 250 kW electrolysis system would need to run at full capacity.

4 Legal and economic analysis

In the following sections relevant topics for authorisation of hydrogen infrastructure in general as well as specific requirements for the presented infrastructure are summarized. Furthermore, an overview of the economic boundary conditions and the key facts of the comparative analysis of the investment are depicted.

4.1 Authorisation process, relevant standards and technical regulations

Beside technical and economic boundary conditions especially highest safety standards have to be met for the implementation and roll-out of hydrogen infrastructure. Legal acts as well as associated technical standards provide the general foundation to meet safety relevant requirements. Based on application different legal acts and standards have to be considered.

Decisive for the identification of the relevant legal matters beside the type of hydrogen infrastructure is also the intended use of the infrastructure, land use planning (zoning) of the side itself and also of neighbouring areas. The operational purpose of the presented plant is cooperative research and development of new hydrogen technologies in the field of non-commercial industrial research and development application at the premises of Graz University of Technologies.

Independent from application and location of the plant, a large number of existing international and national regulations must be observed when planning, constructing and operating decentralised hydrogen systems. They can be categorised into EU legal acts, federal laws and federal ordinances as well as state laws and state ordinances. Nevertheless, there are numerous unresolved legal issues in the field of hydrogen applications. The resulting legal uncertainty makes it difficult for potential installers and operators to realise new hydrogen plants and hinders the rapid implementation of an environmentally friendly energy system, see [6]. Therefore, active inclusion and close cooperation with local authorities is essential for the successful processing of authorisation procedures.

After consultation with relevant local authorities, the procedure for the authorisation process has to be agreed: For the presented project, a building permit has to be applied for the erection of buildings according to [7]. Additionally in Austria, operating facilities must be authorised in accordance with the trade regulation Act [8], if the hydrogen plant is operated as part of a commercial activity. In any other cases the basic safety requirements for gas installations for the production, storage, distribution and use of flammable gases are regulated in various local specific legal standards. Due to the specific type of use at the premises of Graz University of Technology (cooperative research and development) the infrastructure it was agreed that the installation and operation of the presented R&D-infrastructure has to comply with Styrian Gas Safety Act [9]. Finally, an application has to be made for a workplace licence in accordance with the national Employee Protection Act [10].

4.2 Comparative investment appraisal

The presented infrastructure is operated in a highly dynamic and volatile environment of cooperative research and development projects. Consequently, there are major uncertainties concerning operational planning, testing hours and therefore achievable operating hours of the considered systems. Nonetheless, the following investment comparison analysis is carried out from the perspective of commercial use in order to derive the basic statements and characteristic economic key performance indicators which are relevant for economic characterization of such infrastructures in industrial applications. Comparing of different investment scenarios have to consider market mechanism forming international, national and local hydrogen prices.

Hydrogen – Market price development

The hydrogen production costs of current hydrogen production plants are heavily dependent on the technology used, the application environment and the size of the plant. For example, the investment costs for large-scale plants in the US are generally lower than in Europe. The reasons for this include less restrictive environmental regulations, lower land and labour costs and lower taxes. The costs for approval procedures and licenses for operation also vary, see [6].

The following graph illustrates the price history of electricity, natural gas and hydrogen from trailers in Austria. The electricity price forms the basis for the production costs of hydrogen using electrolysis system [6]. A large part of Hydrogen delivered by trailer is produced by natural gas reforming [1]. As depicted in Figure 10, natural gas price has a direct impact on hydrogen price by trailer. A correlation between electricity prices, natural gas prices and hydrogen prices is clearly recognizable. If natural gas prices rise, electricity and hydrogen prices can be expected to rise with a time lag. Hydrogen price reacts faster than price of electricity. It seems that rising natural gas prices are passed on more quickly than falling prices.

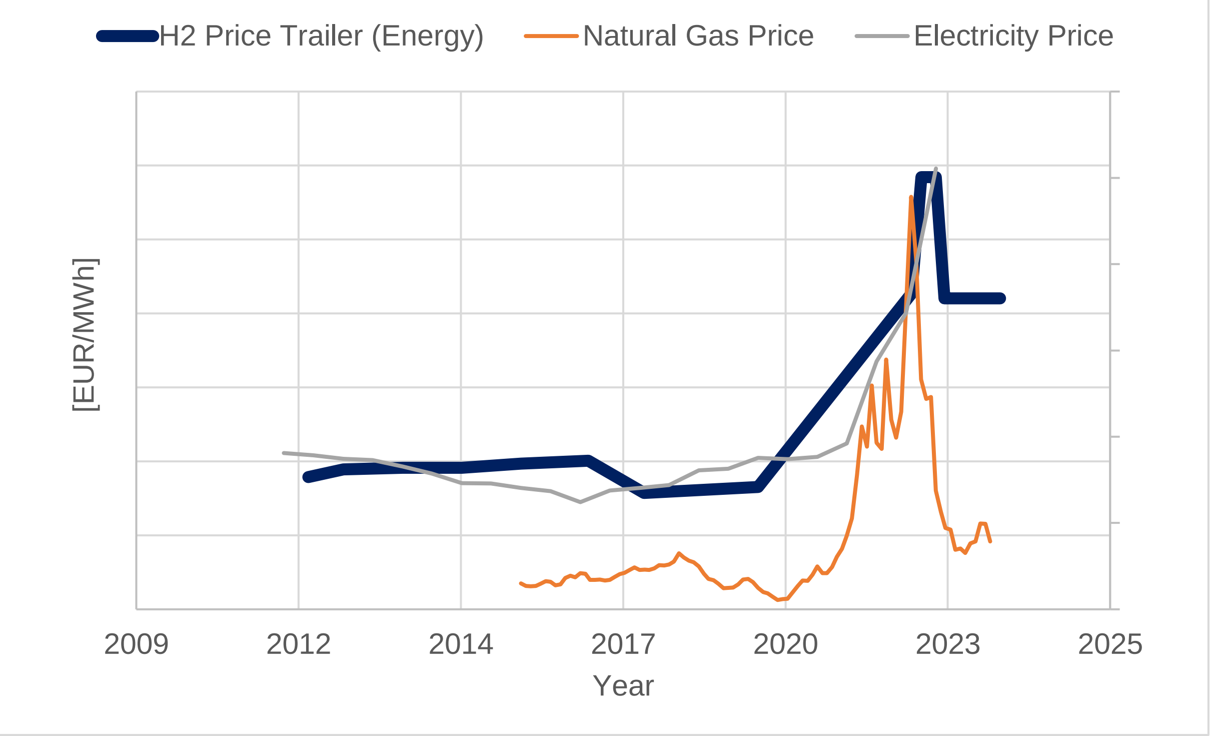


Figure 10: Price histories (energy price) for trailer-hydrogen, natural gas and electricity [11,12]

Based on current market mechanisms, price increases in the natural gas market directly result in price increases for trailer hydrogen (mostly hydrogen from reformer) and also for electrolysis system hydrogen. This has to be taken into account for comparative investment analysis of hydrogen delivered by trailer and onsite hydrogen produced by electrolysis system.

In the long term, the most economical technology will be determined on the one hand by the development of investment costs, the running costs for the required energy sources and on the other hand by environmental policy and the effectiveness of a suitable CO_2 taxation system, see [6,13]

Boundaries and scenarios for cost analysis

The calculation of the specific hydrogen production costs for the following three cost-scenarios listed in Table 6 is based on the method described in ÖNORM M 7140 and EN 15459-1 [14,15].

In Scenario I it is assumed that 100 % of the hydrogen demand is supplied by onsite production with a 1 MW PEM electrolyser. In scenario II the hydrogen demand is covered by a 250 kW electrolyser combined with trailer supply. In scenario III the entire hydrogen demand is covered by trailer supply (no onsite electrolysis system installed). The annual hydrogen production and trailer supply quantities slightly defer from calculated quantities in Table 4 and Table 5 due to the utilisation of the hydrogen demand side management tool shown in section 2. Demand side management is essential to achieve a hydrogen contribution margin of 100 % without oversizing hydrogen infrastructure leading to economic optimized infrastructure configurations.

Table 6: Description of Scenarios for economic analysis and Calculation of Hydrogen Supply Costs with the associated technical scenario summarized in Table 4 and Table 5

Economic Scenario	I	II	III
Short description	1 MW electrolyser; no Trailer	250 kW electrolyser and trailer supply	Only trailer; no onsite production
Corresponding technical configuration in Table 4 and Table 5	Scenario 1	Scenario 4	n.a.
Hydrogen demand [t/a]	50.3		
H_2 Onsite Production [t/a]	50.3	16.6	0
H_2 supplied by Trailer [t/a]	0	33.7	50.3
Number of trailer per year	0	60	78

Table 7 summarises the most important economic parameters for total cost calculation and calculation of hydrogen prime costs. The numbers are based on specifications and best practice indications of the ÖN and EN-standard for complex technical facilities [14,15] as well as empirical values from hydrogen demonstration plants [6].

Table 7: Economic parameters for cost calculation

Considered period	20	a
Electricity Costs	223	EUR/MWh
H_2 Costs Trailer (energy costs)	24.5	EUR/kg
Imputed Interest Rate	2.50	%
Price Increase Rate (system dependent)	0 - 3.5	%

Figure 11 shows the calculated total costs of hydrogen for Scenario I, II and III related to the total costs of hydrogen in scenario I.

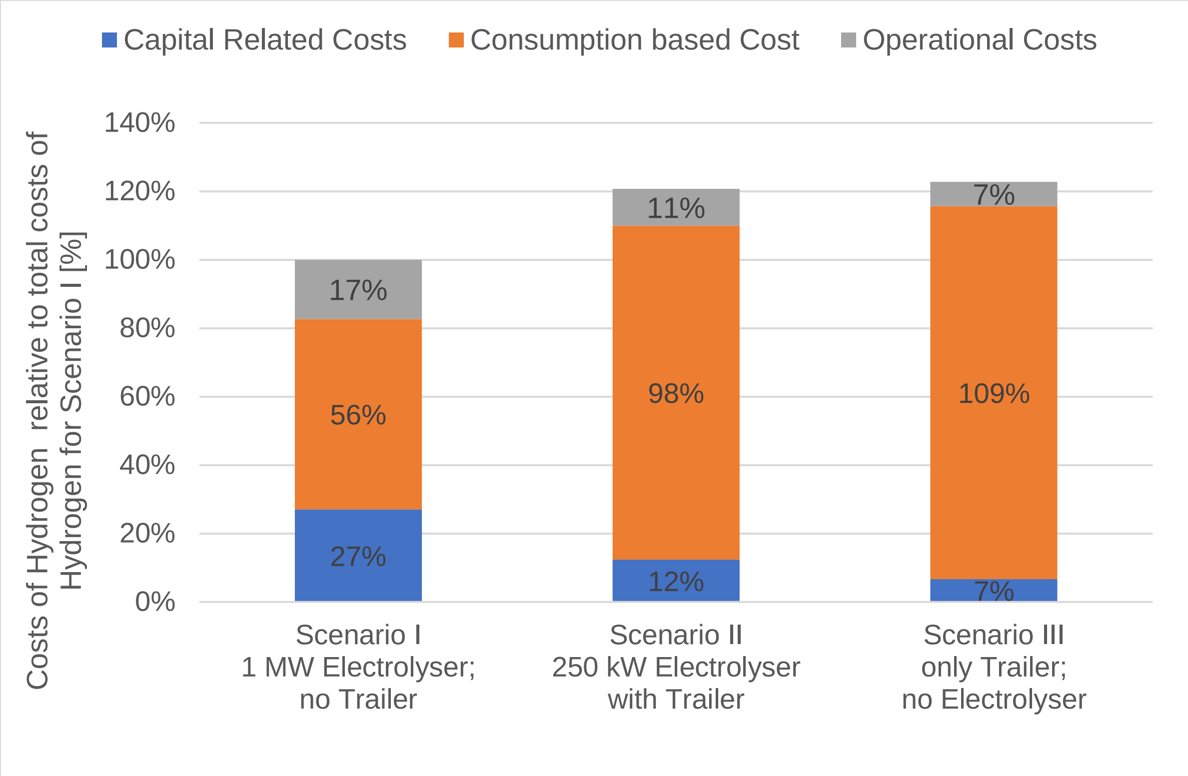


Figure 11: Costs of Hydrogen for considered Scenarios I, II, III related to Total Costs of Hydrogen in Scenario I

Based on the assumptions above onsite hydrogen production with a 1 MW electrolyser is the most economic scenario, although the capacity utilization of the 1 MW electrolyser for that scenario is 32 % corresponding to 2,679 full load equivalent hours a year. The total Hydrogen Costs for Scenario III – pure Trailer supply – are 1.23 times higher compared to Scenario I. Hydrogen costs for the combined onsite Hydrogen production with a 250 kW electrolyser and trailer supply are 1.21 times higher. The utilization rate of the 250 kW electrolyser is 59 % corresponding to 5,000 full load equivalent operation hours a year. Pure trailer supply is in all cases the most uneconomic scenario. The comparable high costs for hydrogen in Scenario II can be attributed to the high specific investment costs of small-scale electrolyser systems.

The illustration in Figure 12 shows the sensitivity of hydrogen production costs of the 1 MW electrolyser system to electricity price and full load equivalent operating hours. The total costs of hydrogen are related to hydrogen cost when delivered by trailer.

As can be seen in the graph for all electricity price scenarios the operating strategy of the electrolyser system should be designed to lead to a capacity utilization of more than 4 000 hours a year. Lower utilizations rates lead to high specific capital related costs and therefore high total costs of hydrogen. Nonetheless, scenario I shows, that even utilization rates with the 1 MW electrolyses system of 32 % (2 670 full load equivalent hrs/a) is more economic compared to scenario III - pure trailer supply. At electricity costs of 50 EUR/MWh even low-capacity utilisation rates of the 1 MW electrolyser in the range of 1 100 operating hours a year leads to lower hydrogen prime costs compared to trailer supply (under the listed assumption for trailer hydrogen listed in Table 7).

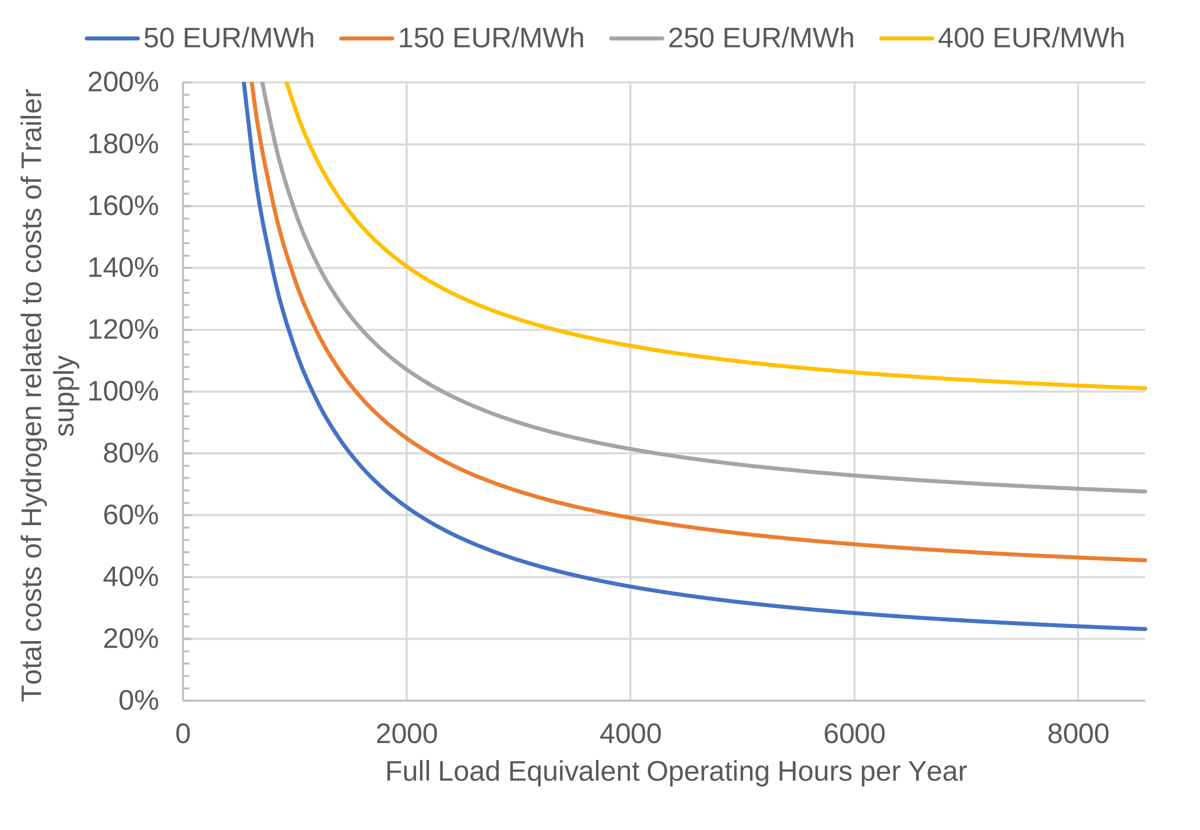


Figure 12: Sensitivity of Total Costs for Hydrogen to electricity prices and capacity utilisation of the 1 MW electrolysis system

5 Summary

A structured method for multilevel and multiparameter based optimisation of complex hydrogen infrastructure was presented. This approach ensures an efficient design process meeting all requirements on a technical, economic, safety and legal point of view. As part of the presented process, a method for the creation of representative hydrogen consumption profiles with highly volatile consumption profiles is presented. Randomized consumption profiles are created with respect to defined boundary conditions from complex demand situations. This enables the statistical analysis of the performance regarding hydrogen contribution margin and self-sufficiency for different facility configuration scenarios. Inclusion of an intelligent hydrogen demand management system enables a cost-efficient design of the whole infrastructure that meet all hydrogen demands 24/7.

For the specific application at Graz University of Technology six technical hydrogen facility configurations were considered. Considering low pressure, medium pressure and high pressure demand the highest hydrogen contribution margins with lowest efforts in onsite hydrogen demand management is met by 1 MW electrolysis system combined with large low-pressure storage (308 kg, 80 bar) and large medium pressure storage (557 kg, 500 bar) – scenario 3. Considering only the low pressure and medium pressure demand, the highest hydrogen contribution margins are calculated for scenario 5 - 250 kW electrolysis system in combination with larger low-pressure storage (616 kg, 80 bar).

Taking into account space restrictions, economic restrictions, legal restrictions as well as contribution margins in combination with the possibility to implement a hydrogen demand side management system, scenario 1 becomes the finally realisable scenario.

For a hydrogen demand of 50.3 t/a the total cost analysis of three scenarios show that pure hydrogen supply by trailer is more expensive than all other scenarios using onsite electrolysis system. Even low capacity-utilization rates with a 1 MW electrolyses system of 32 % (2 670 full load equivalent hrs/a) is more economic compared to the pure trailer supply scenario.

6 Outlook

In a first realization phase the discussed demand-site management tool will be implemented as a simplified prototype system. To minimize manual disposition activities the functionalities and degree of automation of this tool will be gradually extended. One functionality could be the implementation of a direct interface to disposition systems of gas trailer suppliers. Further development potential could be the integration of model predictive control systems in order to enhance storage management. Additional approaches could include AI-driven learning systems for better forecasting the hydrogen consumer behaviour.

Moreover, the demand-side management tool is suitable for meeting the requirements withing the industrial and commercial sectors. However, it needs further development and optimization for effective implementation in these domains.

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