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HyTruck

Hydrogen Truck Austria

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2 Introduction

The key objective of this project was the development of a modular commercial vehicle fuel cell system which can be applied to buses, light-, medium- and heavy-duty trucks.

Main tasks were:

- Development, build-up, calibration and validation of an HD fuel cell system and its key technologies to meet performance, efficiency, reliability, and lifetime criteria of commercial vehicles.
- Novel, innovative, and tailored control strategies for enhancing the fuel cell system performance, efficiency, reliability, and lifetime.
- Novel and innovative superordinate energy management strategies for commercial vehicles to achieve optimum performance, efficiency, reliability, and lifetime of the fuel cell-based powertrain.
- Conceptional design, layout, and thermodynamic simulation of the hydrogen tank system for commercial vehicles.

Comprehensive technical, economic, and ecological analyses were performed to highlight the compatibility to the objectives of the RTI initiative and achievement thereof within HyTruck.

3 Content presentation

The main target was to develop a common understanding of commercial vehicle and trucking business requirements and specification. Based on discussion among the project partners it was mutually agreed that 4 commercial vehicle classes should be considered within the HyTruck project: i) 5-6 ton, ii) 12-18 ton, iii) 26 ton and iv) 40-ton classes. However, since the European vehicle platforms for a 40-ton truck tractor are the most challenging in terms of packages space, power demand, cooling area, etc. it was decided that the main focus is set on this vehicle class. Real-life fleet driving data were recorded and were used for further investigations.

The evaluation of driving cycle and truck powertrain requirements showed that 270 kW fuel cell system power are needed to be competitive to current diesel trucks. A modular fuel cell system (FCS) based on 3 identical 90 kW units was investigated based on existing fuel cell system components on the market. However, it became clear within detailed design studies that packaging limitations on vehicle side (i.e. European 4x2 truck) would not allow to package 3x 90 kW FCS despite initial proof of concept. In order to find a solution to package 270 kW of FCS power into the truck vehicle platform packaging as well as component studies were carried out. Due to new fuel cell components entering the market and an adapted FC stack configuration the FCS power output was increased from 90 kw to 156 kW. After redesign of the FCS a packaging of 2x 156 kW FCS into the truck platform was achieved.

The obtained vehicle data for European 4x2 trucks were additionally analyzed toward different hydrogen storage options. Theoretical calculations have shown that about 40 kg of compressed gaseous hydrogen (700 bar) are possible to store in the conventional tank packaging space, allowing for about 500km single refill-driving range. The filling process of the hydrogen tanks was investigated using 3D CFD simulation. Particularly of interest were the calculated temperatures at the end of the filling process, which must remain below a certain value to avoid failure of material. The main goal of the simulation was to evaluate different pressure increase (i.e. filling) rates, where shorter filling times are obviously desired, while considering the maximum allowed temperature in the tanks after refilling.

Further focus of the project was the development of an adequate energy management system. In hybrid vehicles, the energy management strategy (EMS) distributes the load request to the power sources and it is usually designed to minimize the fuel consumption. In fuel cell electric vehicles (FCEVs), the EMS should also focus on extending the lifetime of the fuel cell system and/or of the battery system. Indeed, due to the higher operational lifetime target of heavy-duty vehicles compared to passenger vehicles special emphasis was put on identifying and developing appropriate control and operation strategies to comply with the target of more than 20,000 operating hours.

Within the comprehensive technical, economic, and ecological analyses the impact of the project on geographical regions (Austria and the region of WIVA P&G) was analyzed. Stakeholders with strongest impact on promoting fuel cells for commercial vehicles were identified as well as legal barriers. The needs for adaptation and specification of the Austrian legal framework on hydrogen and power-to-X were recognized and implemented into WIVA P&G Position paper on legal barriers.

4 Results and conclusions

FEN Systems instrumented fleet vehicles and recorded real-life driving data of 43 DB Schenker trucks. Over 2 months real-life requirements ofauxiliary consumers, e.g. refrigeration systems, was investigated.

Figure 1: Driving profile of the cluster “Commuting” - repeating delivery routes across Europe

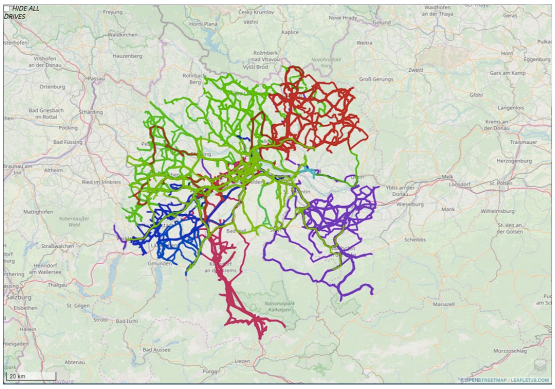

Figure 2: Driving profile of the cluster “Local transport” - delivery around Greater Hörsching

The real-world driving needs were further discussed with truck OEMs. The investigations showed that 270 kW FCS power are required to be compatible with existing diesel trucks. Based on passenger car fuel cell system components, a modular approach with 3x 90kW fuel cell system was pursued, and initial packaging studies indicated that package space of the diesel engine might be sufficient for the integration of the 3 fuel cell systems.

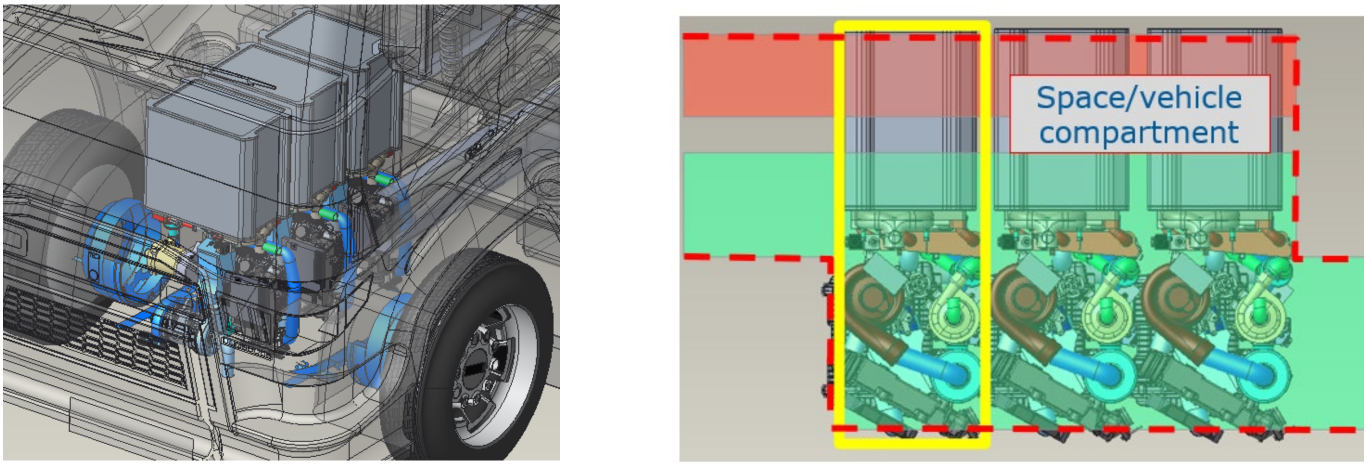

Figure 3: Available vehicle package space and modular fuel cell system concept

The corresponding fuel cell system design was developed and designed.

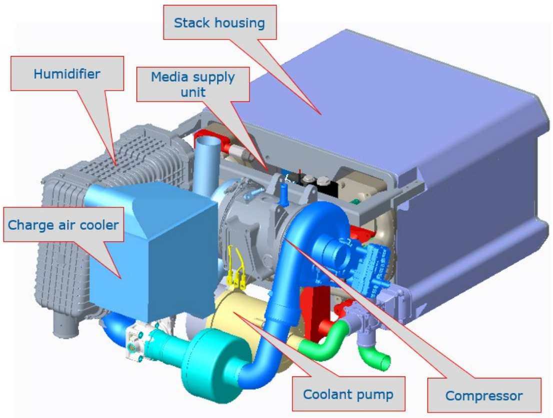

Figure 4: Preliminary modular fuel cell system design and packaging

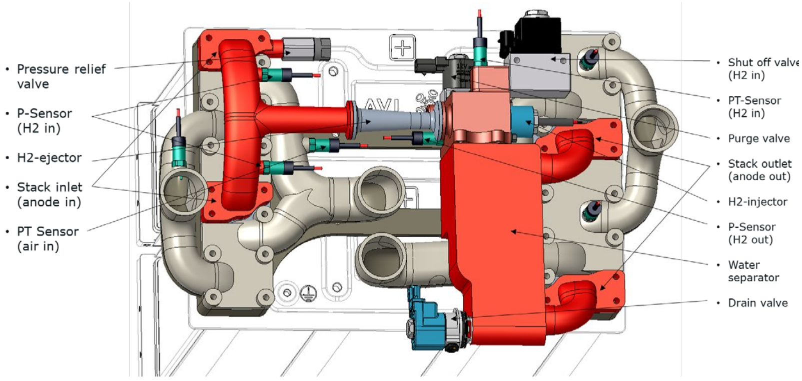

Figure 5: Media Supply Unit – The components described in the picture are part of the anode module designed within HyTruck.

During detailed design studies packaging limitations on vehicle side (i.e. European 4x2 truck) were identified and packaging of 3x 90 kW FCS, despite initial proof of concept, was judged impossible. In order to find a solution to package 270 kW of FCS power into the truck vehicle platform comprehensive packaging as well as component studies were carried out. Due to new fuel cell components entering the supply chain market and an optimized FC stack configuration the FCS power output was increased from 90 kw to 156 kW. After redesign of the FCS a packaging of 2x 156 kW FCS into the truck platform was achieved.

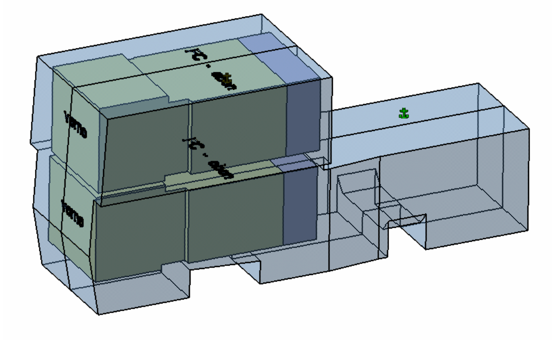

Figure 6: Updated package investigations

Based on the new package space the fuel cell system was redesigned with key focus on power density improvement over competitor fuel cell system on the market, resulting in leading power density of the HyTruck fuel cell system.

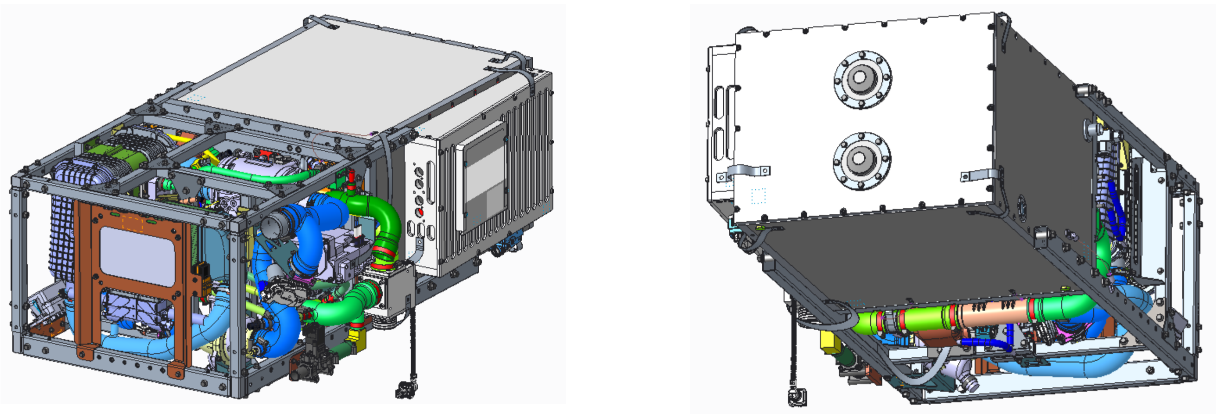

Figure 7: HyTruck – single system with 156 kW power output

The media supply unit was optimized toward functionality with reduced complexity and lower cost.

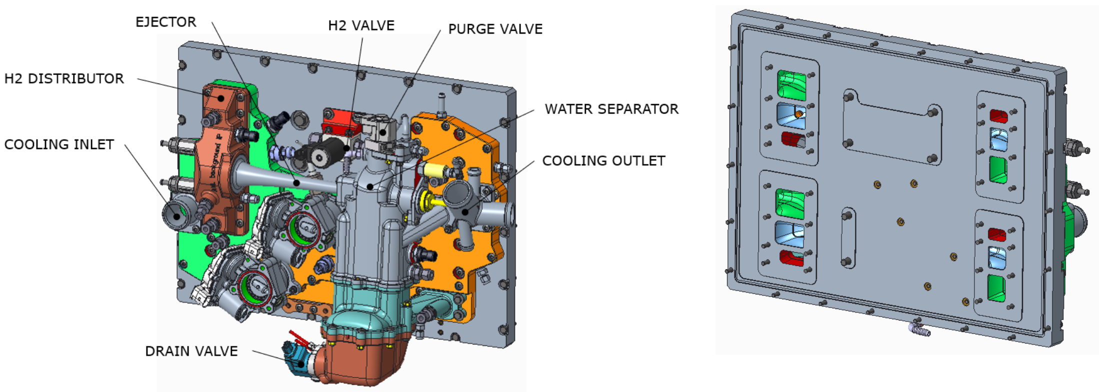

Figure 8: HyTruck – Media Supply Unit

In this system, a volumetric power density of 0.33 kW/L was achieved, which is about a 40% improvement compared to similar systems on the global market.

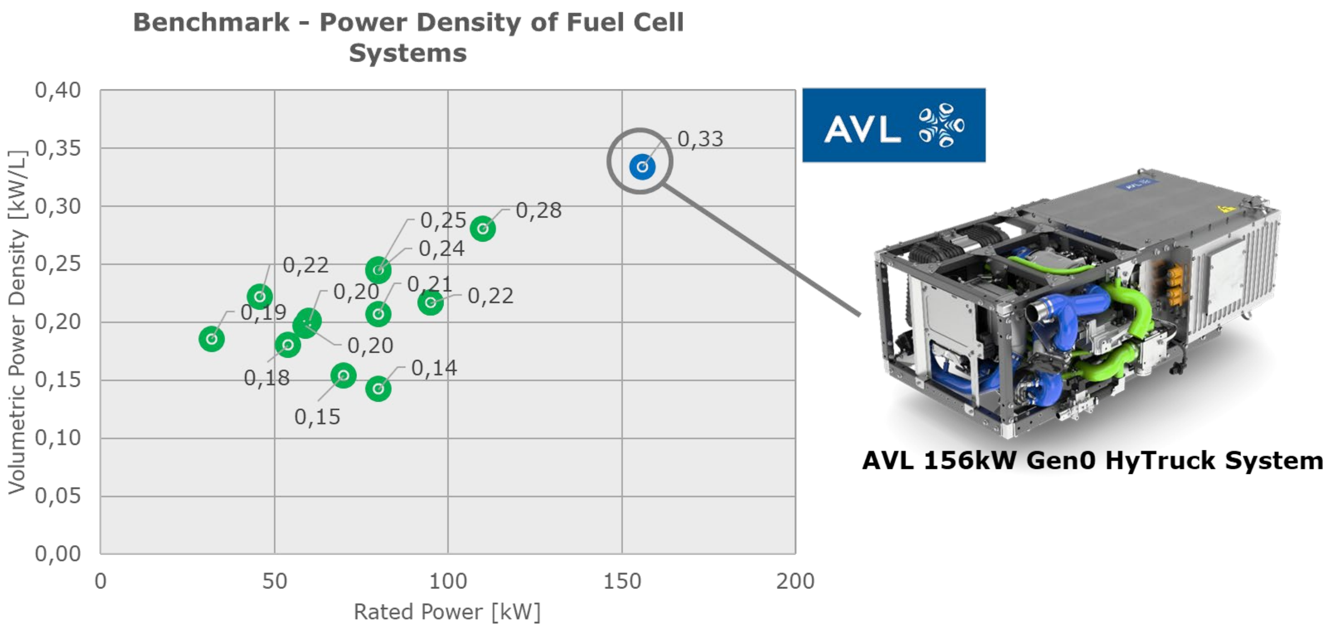

Figure 9: Comparison of the HyTruck fuel cell system with competitor systems on the market

A packaging study for the hydrogen storage, concerning tank design and packaging concept was performed. Based on theoretical calculations about 40 kg of compressed gaseous hydrogen (700 bar) are possible to store in the conventional tank packaging space.

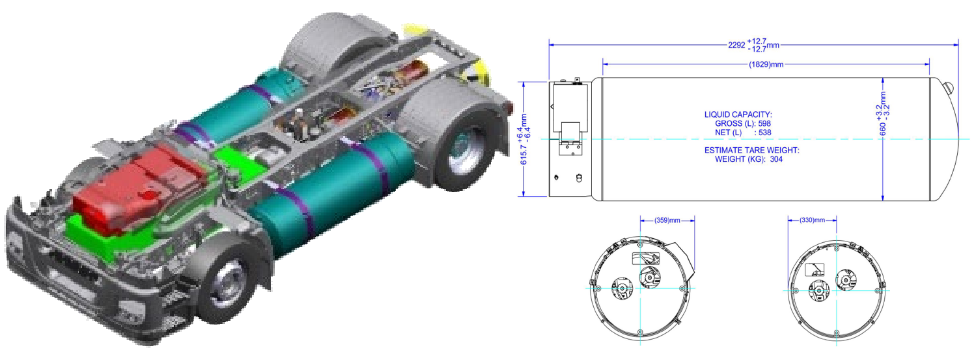

Figure 10: CNG tanks in conventional HD trucks, provided by FPT/Iveco

The filling process of these hydrogen tanks was investigated using 3D CFD simulation software. Particularly of interest were the calculated temperatures at the end of the filling process, which must be below a certain value to avoid failure of material. The main goal of the simulation was to evaluate different pressure increase rates, where shorter filling times are desired, under the maximum allowed temperature constraint.

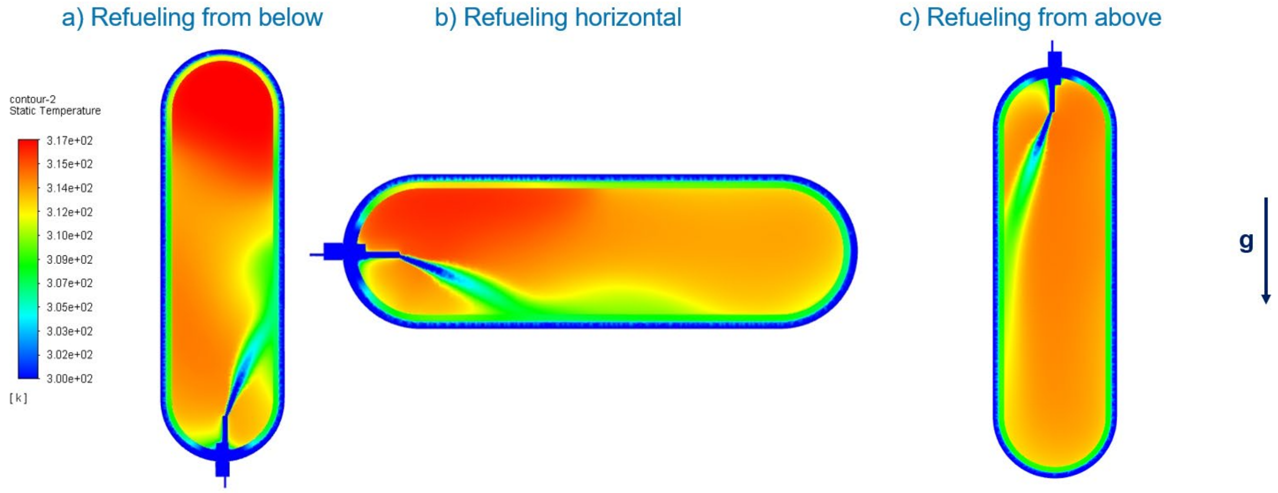

Figure 11: Temperature distribution at the end of filling

A typical temperature distribution inside a tank at the end of the filling process is depicted in above figure. Cold hydrogen enters the tank through the angular inlet and reaches the tank temperature. The temperature distribution in the horizontally placed tank is, of course except for the tank inlet area, uniform. The temperature measurement inside the tanks is typically at the inlet valve. However, it can be seen that hot spots are present for the refuelling from below and horizontal cases, which would not be measured by the temperature sensor at the valve.

Due to the higher operational lifetime target of heavy-duty vehicles compared to passenger vehicles, special emphasis was put on identifying and developing appropriate control and operation strategies to comply with the target of more than 20,000 operating hours. Therefore, the energy management system should be designed to reduce fuel consumption and fuel cell degradation simultaneously. A dual-stage predictive control scheme was identified as the best approach to optimize the performance (see Figure 12). In the first stage, the energy management strategy is optimized at the beginning of the driving cycle based on the speed and elevation forecasts of the navigation system. The optimization results are then stored as predictive references (SoC and FCS power) for the entire route, which the on-board energy management strategy uses in the second control stage.

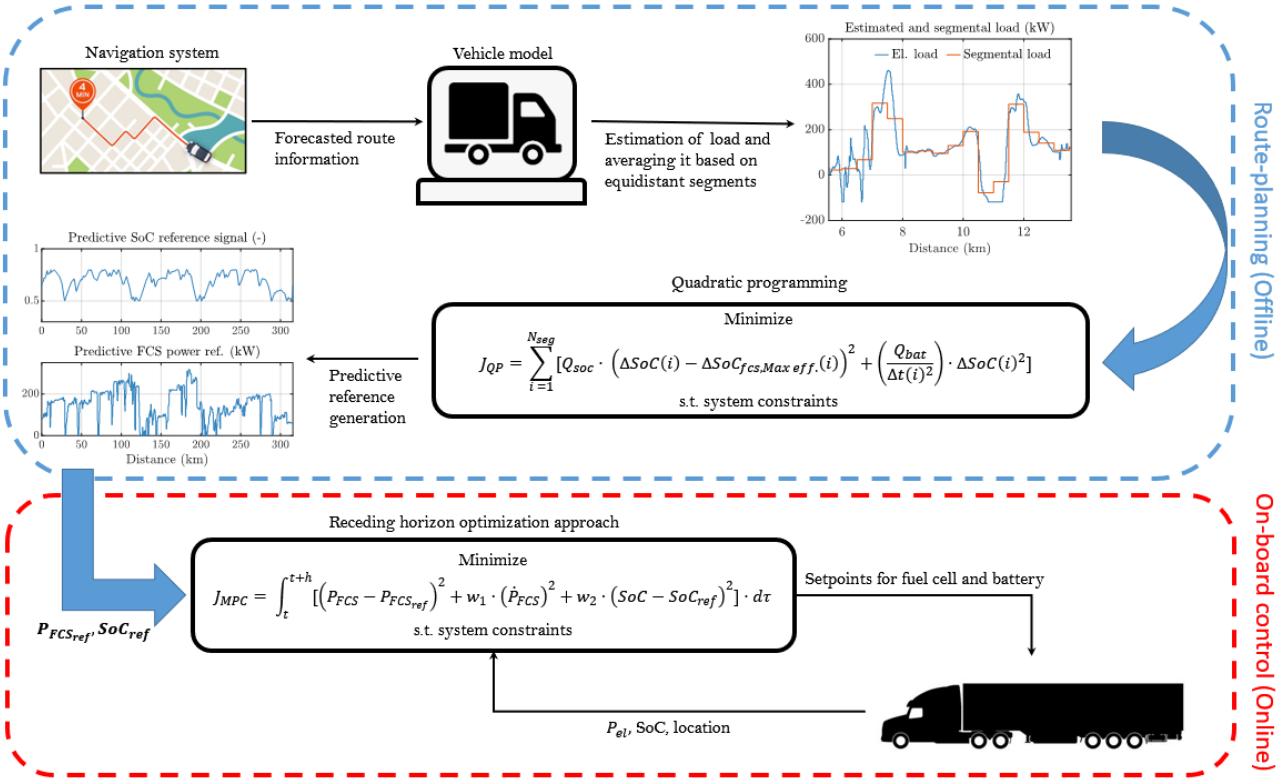

Figure 12: Dual-stage control scheme of the predictive energy management strategy.

The innovative predictive energy management strategy developed in this project significantly improves fuel consumption and reduces fuel cell and battery degradation. In particular, high and low-power fuel cell operations are reduced, and shutdowns are avoided. Moreover, the battery operates within the prescribed voltage, C-rate, and SoC limits, which help mitigate its degradation. An example of optimization results for the predictive energy management references (SoC and FCS power) is shown in Figure 13 for a real-world driving cycle in a challenging route topography. Here, the speed limits are used as route speed forecasts without compromising the accuracy of the electric load forecast because the elevation plays a dominant role.

DB Schenker's data of thousands of driving cycles were used for the statistical evaluation of the simulation results. These driving cycles have a large diversity in duration, average speed, traveled distance, relative positive acceleration (RPA), estimated vehicle mass, and average load. Therefore, considering these vast and realistic driving scenarios enables a robust design and validation of the predictive energy management strategy, increasing the chances of retaining the simulation results' effectiveness after a practical implementation in the actual vehicle.

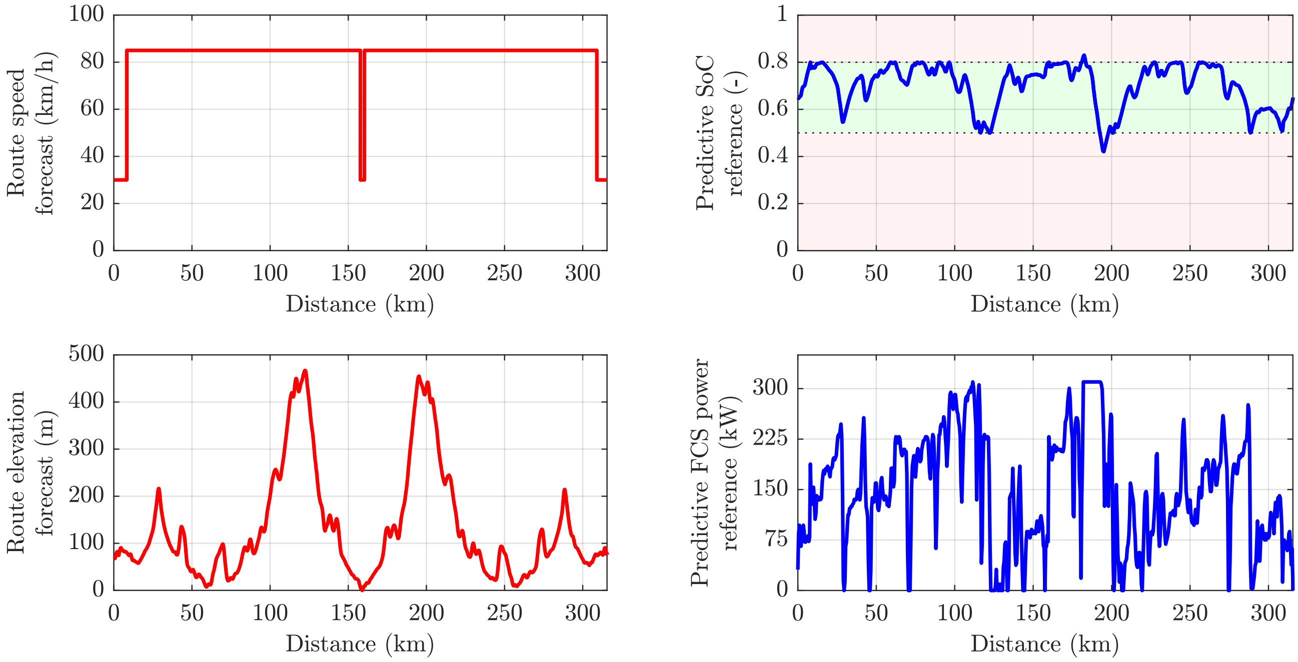

Figure 13: Example of optimization results for the predictive energy management references.

As indicated the thermal management system was a key aspect for the conversion of a diesel truck toward fuel cell propulsion. Eventually, 4 cooling circuits were required in a fuel cell truck: i) high-temperature fuel cell circuit, ii) medium temperature power electronics circuit, iii) low temperature battery circuit and iv) AC circuit. All of these circuits are connected to each other to optimize the thermal management of the entire powertrain. Eg., to utilize the thermal waste heat of the fuel cell for heating the driver cabin and the battery, the thermal management of the battery, the driver cabin and the e-drive components was further detailed and finally integrated into the co-simulation model of the HyTruck project. The integration into the full vehicle model allowed the interconnection of different thermal management circuits. The dimensioning of the heat sinks (e.g. radiators, chiller) and sources (e.g. electric heaters) was done based on the Brenner driving cycle, which also served as a basis for evaluating the capabilities of the simulation model.

The sub-model of the battery thermal management also includes the cabin model, which is shown in Figure 14. The cabin air volume is represented in this model by a plenum component with an energy flow over its boundaries. The considered flows are e.g. the solar radiation or the air mass flow from the ambient. The dimensions of the air volume and the thermal properties of the heat-transferring surfaces were derived from publicly available data and literature. In order to influence the cabin temperature, a heat sink representing the chiller and two heat sources representing the PTC air heater and the heater from the fuel cell coolant circuit were integrated. Several functions and controllers were implemented to reach and keep the required cabin temperature. This sub-model is connected to the fuel cell thermal management model via Model.Connect.

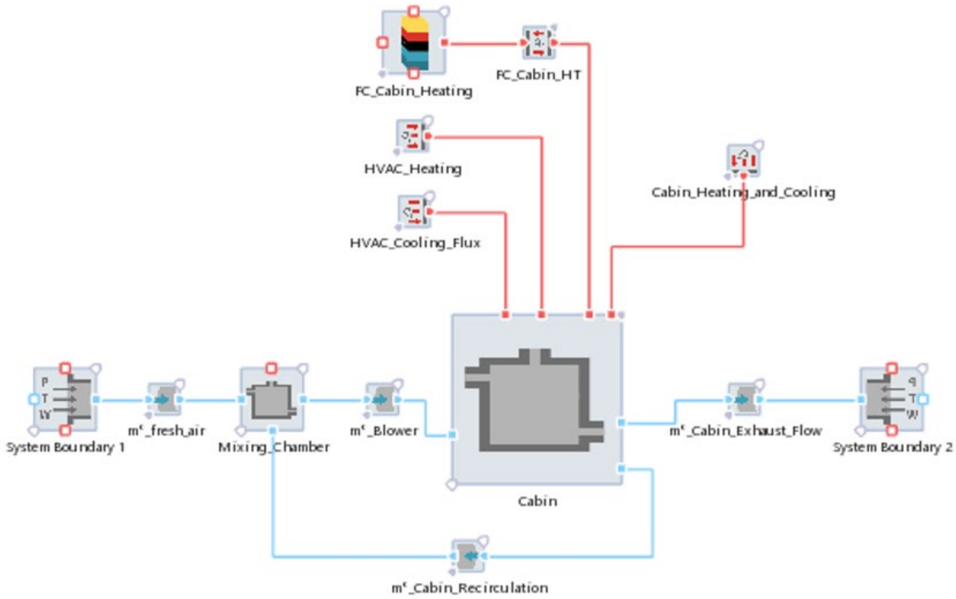

Figure 14: Cabin model in the HyTruck thermal management model

With the modelled battery thermal management circuit it is possible to operate the battery within the temperature window of -20°C up to 40°C. Even though a high-power electric heater and the fuel cell waste heat are used for battery heating, the time to reach a positive battery temperature can take up to 6 minutes and around 13 minutes to operate the battery above the wanted 5°C module temperature (starting from -20°C). The reason for this lies in the big thermal mass of the battery and the constraints in fluid temperature level and temperature spread between battery inlet and outlet. Furthermore, the fuel cell waste heat can only be utilized after the fuel cell itself has reached its working temperature. Therefore, this energy is not available in the first few minutes of the heating process. If the fuel cell waste heat is not used for battery heating, the time for reaching positive temperatures takes almost two hours of operation in the Brenner cycle. In case of not using the fuel cell waste heat, other heating strategies need to be implemented. For the cooling task, the goal of keeping the battery model temperature below 40°C was reached by using the radiator at lower ambient temperatures, a combination of radiator and chiller at medium ambient temperatures (up to approx. 25°C, also depending on the driving profile) and the chiller alone for high ambient temperatures of up to 40°C. The simulated battery coolant outlet and module temperature profile during the Brenner cycle as well as temperature difference between the coolant inlet and outlet can be seen in Figure 15. The module temperature is kept below 40°C to avoid thermal degradation and the temperature difference between the coolant inlet and outlet should not exceed 5 degrees to provide a homogenous temperature profile within the battery module.

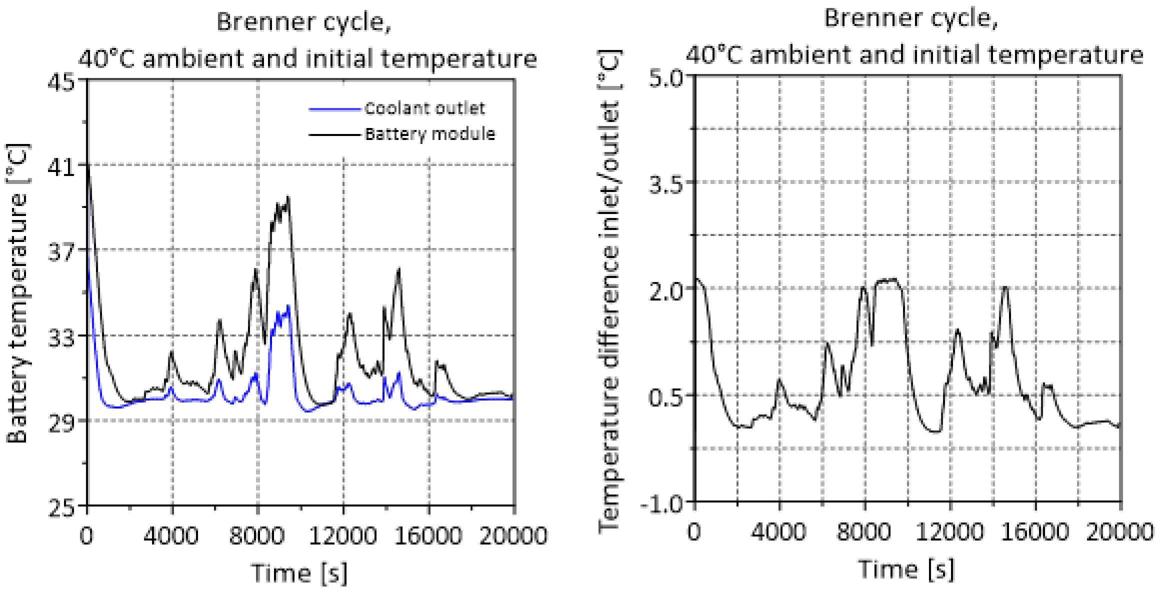

Figure 15: Left: Simulation results of the battery module temperature (thermal model) and the coolant outlet during the Brenner cycle (at 40°C ambient). Right: Battery module temperature difference between inlet and outlet

The fluid circuit was adapted to the final configuration of the HyTruck vehicle. On one fluid branch, the inverters and the electric motors are cooled. The second branch is used to cool the boost converters of the fuel cell. All components can be kept within the allowed temperature boundaries by this configuration. No heating device was installed in the e-drive thermal management model since low temperatures are not considered critical here. Figure 16 shows the temperature curves of the electric motor, the inverter and the fuel cell boost converter during the Brenner cycle.

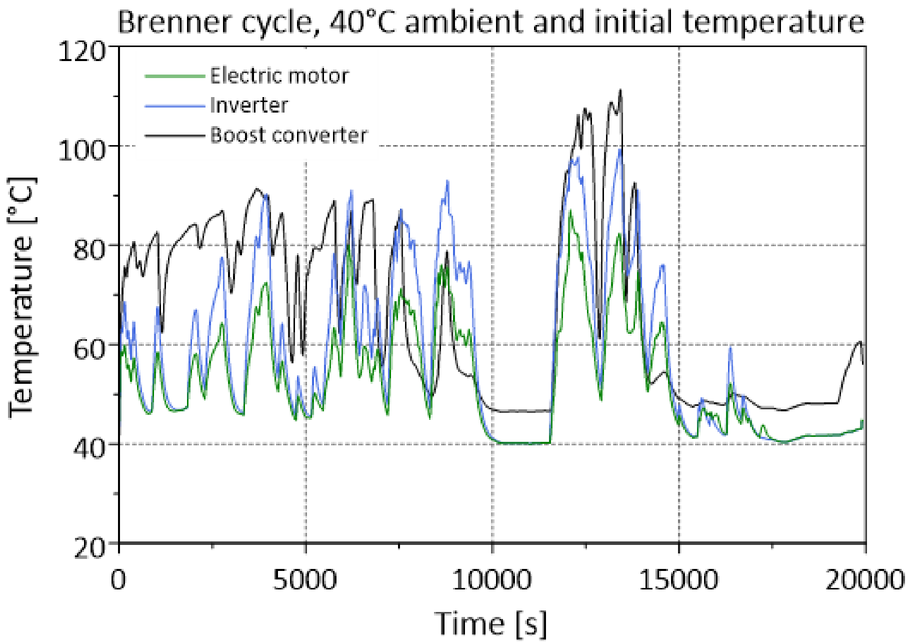

Figure 16: Resulting temperature curves of the ETMS simulation

Furthermore, the project was continuously challenged with the goals of WIVA P&G to identiy the impact of the project on the future energy scenario in Austria. The scientific monitoring and accompanying technical, ecological and economic analysis developed and described possible roll-out scenarios for hydrogen fuel cell trucks in Austria. The resulting total investment costs for the hydrogen fuel-cell trucks and the refuelling station infrastructure, as well as the required hydrogen demand, form the basis for the macroeconomic analyses.

The roll-out scenarios, a moderate and a progressive scenario, were developed based on a comprehensive meta-analysis of the future number of hydrogen fuel cell trucks and their share of the total fleet. Furthermore, a lot of different parameters, which are often very strongly interlinked and influence each other, e.g. climate and energy policy, the total cost of ownership, market readiness, and development of other alternative propulsion systems, were taken into account.

In the moderate scenario, the amount of hydrogen fuel cell trucks increases by 2030 to about 1.000. In the following years, there is a slightly stronger continuous increase, resulting in about 5.400 hydrogen fuel cell trucks registered in Austria in 2040 and about 11.400 in 2050. The progressive scenario has a similar, but steeper, trajectory, resulting in the number of hydrogen fuel cell trucks in Austria being about 3.400 in 2030, about 18.000 in 2040, and about 40.000 in 2050.

As a result, a total of 2.1 billion € is invested in hydrogen fuel cell trucks in Austria in the moderate and 7.1 billion € in the progressive roll-out scenario, as depicted in Figure 17.

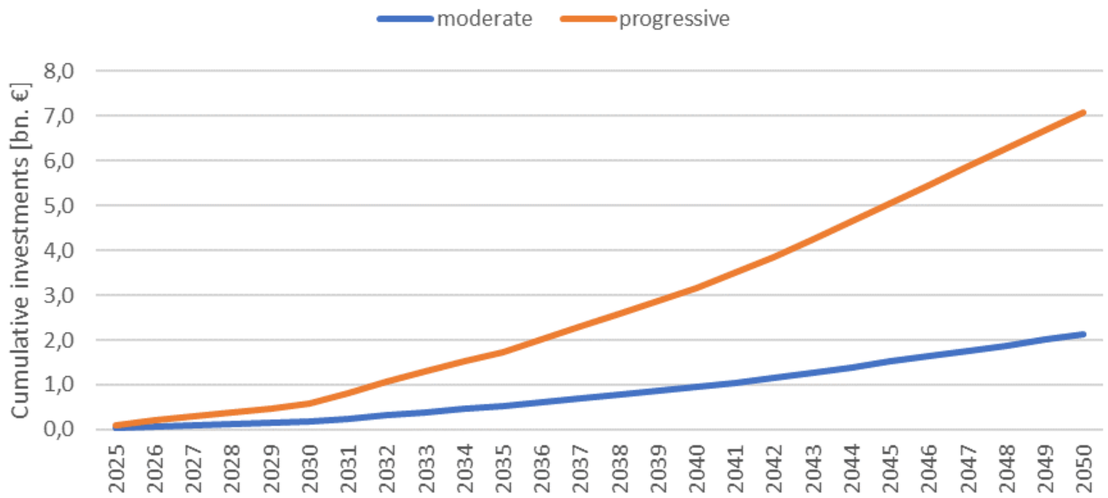

Figure 17: Cumulative investments in hydrogen fuel cell trucks (rigid trucks class N3 and tractor-trailers) in Austria in the moderate and progressive roll-out scenario until 2050

If the moderate roll-out scenario occurs, about 5.700 t/a of hydrogen are needed to supply the hydrogen fuel truck fleet in Austria in 2030, about 29.000 t/a in 2040, and about 59.000 t/a in 2050. Due to the larger fleet in the progressive scenario, significantly more hydrogen is needed, in 2030 about 19.000 t/a, in 2040 about 96.000 t/a, and in 2050 about 195.000 t/a, as portrayed in Figure 18.

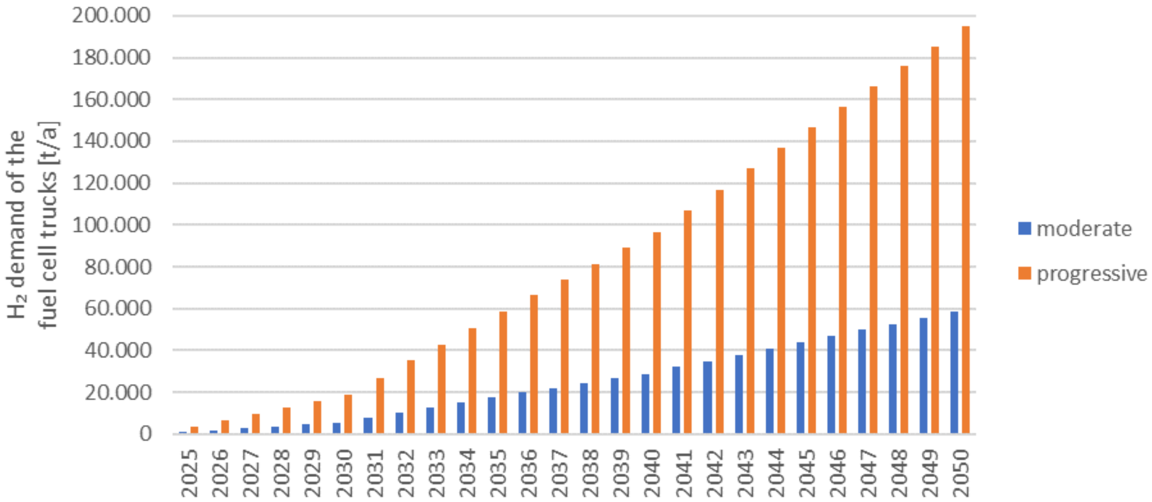

Figure 18: H2 demand of the hydrogen fuel cell truck fleet in Austria

In parallel with the hydrogen fuel cell truck fleet, also the hydrogen refuelling infrastructure must develop. Regardless of the roll-out scenario, around 30 hydrogen filling stations will be built in Austria by 2050, which theoretically means that the maximum distance to the next filling station will not be more than 30 km. However, the two scenarios differ in the amount of hydrogen dispensed to fulfil the hydrogen demand of the fleet. As a result, till 2050 a total of 500 million € is invested in hydrogen refuelling stations in Austria in the moderate and 1.750 million € in the progressive roll-out scenario, see Figure 19.

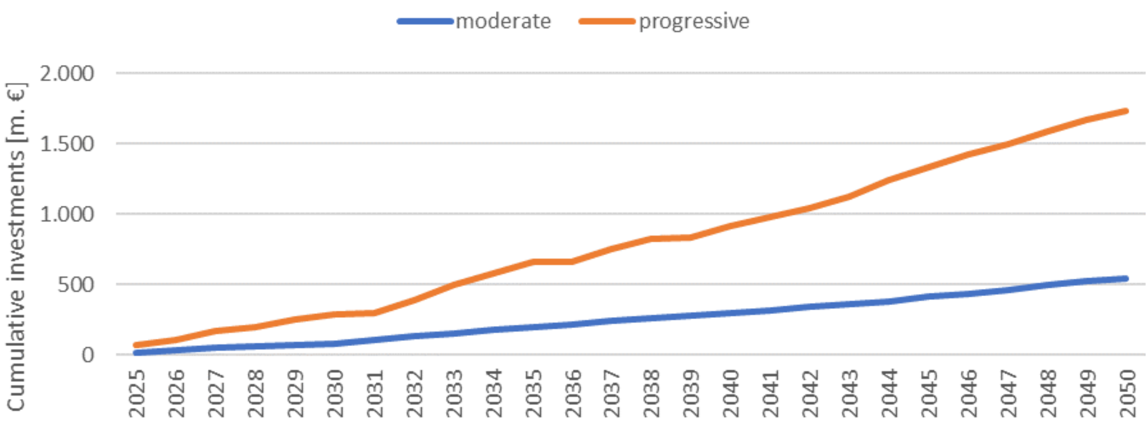

Figure 19: Cumulative investments in hydrogen refueling stations for trucks (rigid trucks class N3 and tractor-trailers) in Austria in the moderate and progressive roll-out scenario until 2050

The macroeconomic and socio-economic impact assessment comprises results of simulation analyses of macroeconomic effects at the Austrian level through the expansion of the FC truck fleet until 2050. The simulation was made with the in-house developed simulation program MOVE (macro-econometric simulation tool). In comparison to the techno-economic analyses, the focus was not on the micro level (end consumer, companies), but the entire economy of Austria. In particular, the effects of investment impulses due to the expansion of the FC truck fleet and the implementation of the required H_2 refuelling infrastructure and domestic trade balance effects resulting from the substitution of imported diesel by H_2 were examined and quantified.

Based on the results of the ex-ante simulation analyses, positive effects on the Austrian economy through an expansion of the FC truck fleet and the necessary refuelling station infrastructure were identified, as seen in Figure 20. For the period 2025-2050, the *moderate* scenario results in the additional economic growth of 77 million € per year and an increase in employment by an additional 2.800 employees per year. For the *progressive* scenario, there is an additional economic growth of 270 million € per year and an increase in employment by an additional 9.200 employees per year.
These positive effects are mainly due to the following general drivers:

- Investment impulses through expansion of the FC truck fleet as well as the H_2 refuelling station infrastructure;
- Decrease in diesel imports due to the use of (partly domestically produced) H_2 and thus positive effects on the trade balance / net exports, which override the negative effects (import due to truck fleet expansion and H_2 use);
- Multiplier effects.

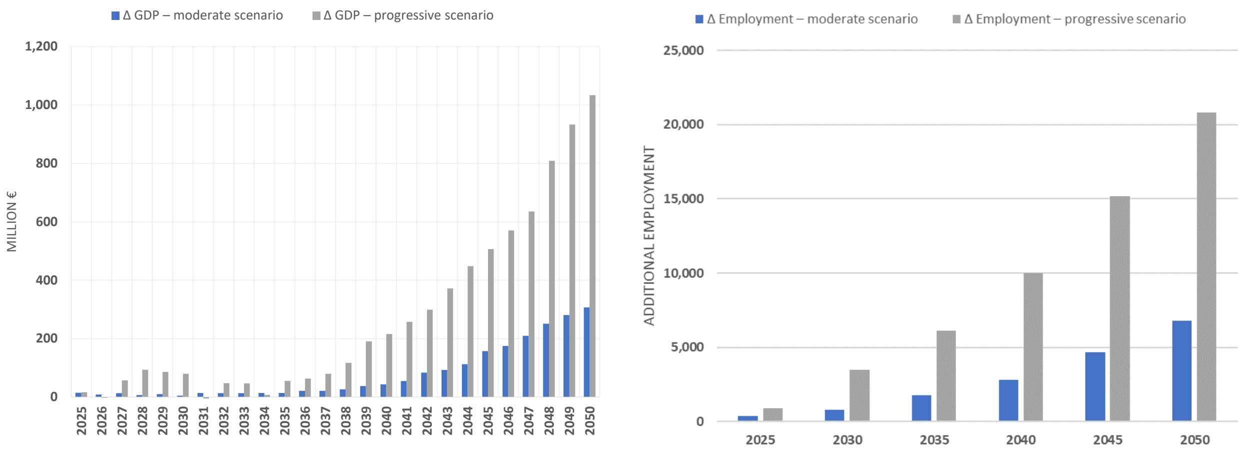

Figure 20: GDP and employment effects in Austria through the expansion of the FC truck fleet and the implementation of the necessary H2 refueling infrastructure

In the well-to-wheel (WTW) Life Cycle Assessment (LCA) study, emissions had been compared for two truck types and two different power trains, i.e. a 40 t gross vehicle weight (GVW) trailer-truck and a 12 t GVW rigid truck with a fuel cell and a diesel powertrain; where the lifespan of the two truck types differed greatly.

For the fuel cell trucks, three different hydrogen pathways had been analysed, with the main variation stemming from the electricity used for electrolysis through a PEM electrolyzer. Thus, a pathway based on the Austrian grid mix, Austrian green electricity (comprising of wind and PV); and the EU-27 average grid carbon intensity had been assessed and compared to the impact of diesel production with its consequential emissions to air during the operation phase of the trucks.

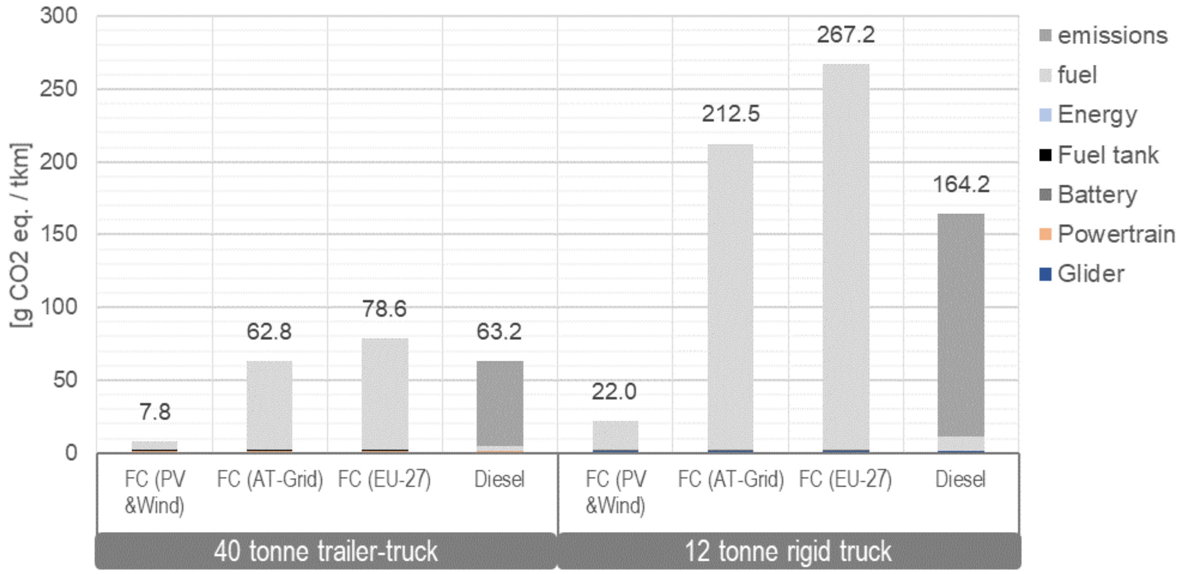

Figure 21: Life cycle Greenhouse Gas emissions, expressed in g CO2-eq. / t-km

From the ‘t-km’ results, it had been identified that the trailer-truck proves to be the more environmentally friendly option for use cases where a long-haul truck is required, considering that the payload is almost 4 times higher than that of the 12 t trucks (25.1 vs 6.3 t). For the fuel cell truck scenarios, the global warming potential (GWP) highly depends on the electricity source used for electrolysis, which resulted in the carbon intensity of 1.87-, 20- & 25.3 kg CO2e/kg H2 respectively for the green-, AT grid- and EU-27 grid electricity sources. Thus, the green electricity scenario yields an 8.1- and 7.5 times lower carbon footprint respectively for the 40 t and 12 t trucks compared to the diesel alternative. The environmental hotspot components for the FC trucks had been associated with the fuel cell (FC) stack and the Li-ion battery, with a respective GWP contribution of 30% and 12% to the total manufacturing GWP.
Future assessment could be focused on the inclusion of the decarbonized Austrian grid mix and the Euro 6 emission standard trucks, where the green H2 scenarios would gain less advantage compared to the fossil-free electric grid aimed to be achieved by 2030. Additionally, as the trend of the fuel cell trucks already indicates a decrease in fuel consumption, the future analysis has the potential to be even more advantageous over the alternative diesel trucks.

The tool SAMBA - developed by the Energieinstitut for qualitative socio-technical assessments – was applied to identify potential obstacles and views in order to be able to take appropriate measures to tackle the challenges. The scope and boundaries for the analysis were set. The geographical region is Austria or specifically, the region of WIVA P&G and the object of investigation is an HD Fuel Cell System, which is modular and equipped with storage for hydrogen. The timeframe in which the analysis takes place is from 2020 to 2030 because in this frame major steps regarding decarbonization should take place. Comparable systems and benchmarks are conventional engines based on Diesel, CNG/LNG and Battery. The results of the sociotechnical assessment (SAMBA) can be seen in Table 1.

Table 1: Sociotechnical assessment (SAMBA) results

	STRENGTHS	WEAKNESSES
SAMBA Matrix	▪ Larger vehicles with long driving ranges benefit from fuel cells. ▪ Daily mileage of 300-400 km for regional transports can be reached. ▪ Weight is lower than battery system and thus higher payload possible. ▪ Modular approach drives wide range of commercial use cases. ▪ Life cycle GWP emissions per km are much lower than for diesel. ▪ Fuel cell trucks are less critical concerning raw materials compared to battery trucks. ▪ Innovative zero-emission solution for commercial vehicles within Europe and the energy model region.	▪ Commercialisation is with TRL 7 at an early stage and due to missing know-how, unforeseen problems are possible. ▪ Fuel cell trucks are more dependent on a network of refuelling stations compared to battery trucks. ▪ Similar driving range to diesel and flexibility as key factors can be an issue. ▪ GWP per kilometre for manufacturing is currently lower for a comparable diesel. ▪ Cost-neutrality is the main decisive criterion as nobody of the customers won't pay a higher freight rate for zero-emission transport services and goodwill is not in the first place.
OPPORTUNITIES	**STRENGHTS /**	**WEAKNESSES /**
▪ Administrative and political stakeholders estimated as "supporters" or "neutral". ▪ Producers and operators of hydrogen filling stations as "supporters". ▪ "Asian & US OEM" are estimated "neutral". ▪ Zero-emission systems will play an important role in the transformation process. ▪ There is no longer any fear of hydrogen. ▪ Acceptance of fuel cell vehicles is considered to be very high. ▪ Customers honour zero-emission transports. ▪ Maintenance costs are expected to be lower than comparable diesel in the future. ▪ Financial support or subsidies are the most important trigger for investments.	▪ Communication strategy, that an investment in fuel cell trucks can be interesting for companies as customers honour zero-emission transports and that can result in a competitive advantage for them. ▪ Active contacting with different industries, as the fear of hydrogen does exist neither at company level nor from the customer side. ▪ Communication to political and administrative bodies, that besides the much lower life cycle GWP emissions per km compared to diesel, also the welfare effects will rise under different scenarios till 2050. ▪ Clear announcement to different stakeholders, that the innovative zero-emission solution for commercial	▪ Active contacting with administrative and political stakeholders for more tests in real transport operations to increase the TRL as fast as possible. ▪ Establishing a partnership and cooperation with producers and operators of hydrogen filling stations to create a network for fast and easy refuelling. ▪ Measures have to be taken, to bring down the GWP per kilometre for the manufacturing phase. Currently, a diesel delivers a better result here. ▪ Exchange with stakeholders that cost-neutrality is the main criterion for companies as customers will not pay a higher rate for zero-emission services. ▪ Active research concerning driving range extension of fuel cell trucks as it is a key success

▪ Toll exemption as competitive advantage. ▪ In the medium term, the investment can pay off and create a competitive advantage. ▪ Welfare effects for Austria will rise under different scenarios till 2050. ▪ Austria's "Mobilitätsmasterplan 2030" stick to 100 % zero-emission registrations by 2035.	vehicles sticks to 100% of Austria's "Mobilitätsmasterplan 2030".	factor.
THREATS	**STRENGTHS / THREATS**	**WEAKNESSES / THREATS**
▪ No experience from existing projects. ▪ Lack of information on different levels. ▪ Customers asking for zero-emission solutions but not specifically for fuel cell trucks ▪ Almost the entire transport industry suffers from financial problems and very low margins. ▪ Impact on the existing network and positions on the market of logistic operations. ▪ Well-established logistics structures will be transformed due to fuel cell trucks. ▪ Negative experiences with LNG trucks as barrier for fuel cell trucks. ▪ Number of refuelling stations is a bottleneck that can't be solved in the mid-term. ▪ Major challenges due to increasing demand and import dependency for materials. ▪ Planning certainty, as well as exchange of opinions from the political side, is lacking.	▪ A clear communication strategy with all the advantages compared to diesel as well as an LNG truck is needed. The negative experiences with LNG are a barrier. ▪ Demonstration of various use cases that the modular approach and the use of a fuel cell truck in daily operation does not change the usual logistics structures ▪ Clearly communicate that fuel cell vehicles are less raw material critical compared to battery vehicles and no major challenges due to import dependency expected. ▪ The embedding of the project in the Energy Model Region and the national strategy should be used to overcome the planning security and the lack of exchange.	▪ Development of different strategies to accelerate operations in real logistics environments to gain experience and generate momentum for investments. ▪ As fuel cell trucks compared to battery trucks are more dependent on a network of refuelling stations this bottleneck can't be solved in the mid-term. This problem has to be pushed and discussed on a higher administrative and political level. ▪ Clear costs for fuel cell vehicles both in acquisition and operation are not available and this lack of information on different levels leads to problems in calculating the vehicles. Therefore, clear and realistic information is needed that companies can work with.

The stakeholders were identified and structured into seven different groups (Administration, Politics, WIVA P&G, Associations & NGOs, Economic players, Press & Media and Civil society). All the stakeholders have been assessed according to their influence (power to change the direction of the project), importance (active or passive interest in the project) and general attitude towards the project with the help of experts and consortium members. Most of the stakeholders are expected to have a "neutral" or "positive" attitude toward the project. In total, no opponents exist but four stakeholders may have an ambivalent attitude which means that they are maybe asking for background information or are focused on possible critical points of the project.

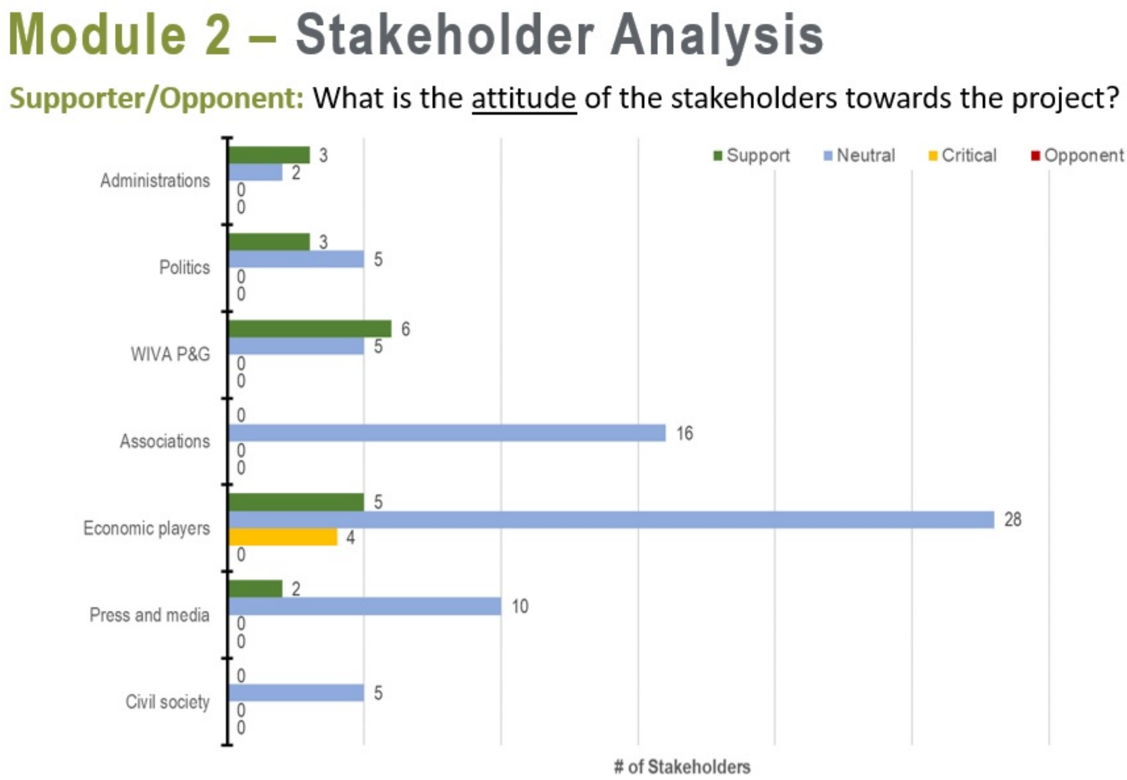

Figure 22: Results of stakeholder analysis

According to the evaluation of the respondents, all four stakeholders only have to be monitored and not managed closely with special strategies. This means that they can't be seen as decisive, as little influence and importance are attached to them. In total, the creation of the project can be seen as a positive and supportive step concerning the different international and national climate and energy targets.

Within the legal analysis, the European and Austrian legal bases, strategies as well as subsidies in the field of hydrogen in mobility were examined with a focus on heavy-duty transport. In addition, a position paper was prepared together with AVL List GmbH, Energie AG Oberösterreich, Energie Steiermark Technik GmbH, EVN AG, FEN Research GmbH, Fronius International GmbH, HyCentA Research GmbH, K1-MET GmbH, OMV Refining & Marketing GmbH, RAG Austria AG, Verbund AG, voestalpine Stahl GmbH, Wiener Stadtwerke GmbH und WIVA P&G and published by WIVA P&G. In this paper, proposals for the amendment and specification of the Austrian legal framework on hydrogen and Power-to-X were elaborated. In the chapters "Charges and Tariffs", "Certification", "Plant Construction", "Infrastructure" and "Refueling", proposals for measures were formulated and respective authorities for their implementation were named. Furthermore, a working group "Authority Procedures" was established to identify and discuss barriers and possible solutions in the area of authority procedures, taking into account the applicable legal framework.
At the European level, provisions on renewable hydrogen can be found in particular in the TEN-T Regulation (Regulation (EU) No. 1315/2013 as amended by 2019 L 43/1), in Regulation (EC) No. 79/2009 as amended by 2019 L 198/241, in the Directive on the promotion of clean road transport vehicles in support of low-emission mobility (Directive 2009/33/EC as amended by 2019 L 188/116) and

in the Directive 2014/94/EU on the deployment of alternative fuels infrastructure (as amended by 2019 L 268/1). The Renewable Energy Directive II (Directive (EU) 2018/2001 as amended by 2019 L139/1) also includes relevant provisions for hydrogen in the transport sector.
Austria has implemented the European provisions on alternative fuels, corresponding infrastructure, and the promotion and integration of clean road transport vehicles. The provisions have been adopted into law through the Uniform Alternative Fuels Infrastructure Development Standards Act (F.L.G. I No. 38/2018 as amended by F.L.G. I No. 150/2021), the Road Vehicle Procurement Act (F.L.G. I No. 163/2021), and the Motor Fuel Ordinance 2012 (F.L.G. II No. 398/2012 as amended by F.L.G. II No. 630/2020), among others.
The RED II sets a sector-specific target for the transport sector and specific calculation rules for it. The relevant provisions have been set out and analyzed. Furthermore, the provisions introduced by the Renewable Energy Expansion Act on renewable gas certificates, which enable verifying the production of renewable gas that is not fed into the public grid, as well as the renewable gas badge were described. In addition, the requirements to standardize the approval and registration procedures of class M and N vehicles were included as part of the analysis. Moreover, the financial facilitations and subsidies in the project-relevant context are to be emphasized. With regard to subsidies for hydrogen-powered vehicles and hydrogen refuelling stations, research was conducted at the federal and state levels and comprehensive findings were presented within the legal analysis. There are exemptions for hydrogen and electrically powered vehicles, such as exemption from the standard fuel consumption tax, and the vehicle tax. Reliefs are also provided in the natural gas tax (F.L.G. I. No. 201/1996 as amended by F.L.G. I. No. 103/2019), in the Immission Control Act-Air (F.L.G. I. No. 115/1997 as amended by F.L.G. I. No. 73/2018), such as the exemption from the speed limit on the highway, and in the Value Added Tax Act (F.L.G. No. 663/1994 as amended by F.L.G. I. No. 112/2021) the input tax deduction, are provided.

5 Outlook and recommendations

From the SAMBA matrix, the following strategies and recommendations for the project **HyTruck** and the development of fuel cell trucks are derived.

Communication & Stakeholder Engagement

- Active contacting of various industries (not only focussing on heavy-duty road transport), as the modular design of the system allows a wide range of applications. As basically the fear of hydrogen does exist neither at the company level nor from the customer side, the opportunities for a broad introduction across diverse sectors are increasing.
- Communication to administration and political bodies that besides the much lower life cycle GWP emissions per km by using renewable hydrogen compared to diesel, also the welfare effects for Austria will rise under different scenarios till 2050. Fuel cell trucks are therefore a big advantage.
- Clear announcement to administrative and political stakeholders, that the innovative zero-emission solutions for commercial vehicles fit 100 % to Austria's "Mobilitätsmasterplan 2030" with 100 % zero-emission registrations by 2030 respectively 2035. From today's perspective, investments in such sustainable technologies need to be strongly pushed.
- The embedding in the Energy Model Region also can be used for targeted information (events, magazines, commercials etc.) to freight transport companies to show them the latest results from field tests and demonstration projects, so that they can close their currently existing knowledge gap.
- Exchange with administrative and political stakeholders that cost-neutrality is the main decisive criterion for companies as customers are not willing to pay a higher freight rate for zero-emission transport services. Therefore, financial support or subsidies like toll exemption can bring competitive advantages when using fuel cell trucks.

Acceptance

- A clear communication strategy with all the qualitative and quantitative advantages respectively facts of a fuel cell truck compared to a diesel truck as well as an LNG truck is needed. The negative experience with LNG is in many cases a barrier to investment in zero-emission trucks at the company level.
- Demonstration and dissemination of various use cases that the modular approach of the project and the general use of a fuel cell truck in daily operation does not or only insignificantly change the usual logistics structures.
- Active networking and involvement of administrative, political and economic stakeholders for more tests in real transport operations are needed to increase the TRL 7 as fast as possible. This possibility has a high chance to reduce the active barriers concerning investments in fuel cell trucks and these above-mentioned stakeholders are generally interested in the technology.

Technological development

- Due to the reason that fuel cell trucks will play an important role in the transformation process to climate neutrality, measures have to be taken, to bring down the GWP per kilometre for the manufacturing phase. Finding alternatives to carbon-intensive materials in the fuel cell (platinum) and the battery (Li-NMC) is of high importance and could lower the manufacturing footprint significantly. Another, more evident measure to lower the manufacturing impact, would be to enhance the lifetime of the fuel cell trucks.

- Active research concerning driving range extension of fuel cell trucks is needed as it is compared to diesel as a key success factor. In general, the acceptance of fuel cell vehicles is already very high.
- Development of different strategies to accelerate operations of fuel cell trucks in real logistics environments to gain technical know-how and experience and generate momentum for investments. Missing practical and operational information can lead to unforeseen technical disturbances.

Economics

- Provide transparent decision support tools for freight transport companies on alternative propulsion technology with a transparent communication of needed operational and organizational adaptions as well as showing the cost effects.
- Clear costs for fuel cell vehicles, both in acquisition and operation, are not available and this lack of information at different levels leads to problems in costing the vehicles. Therefore, clear and realistic information is needed for companies and decision-makers to work with.
- Communication strategy, that an investment in fuel cell trucks can be a good use-case for companies as customers already honour zero-emission transports and that can result in a competitive advantage.

Infrastructure

- The embedding in the Energy Model Region and therefore the national strategy should be used to overcome the planning insecurity and the lack of exchange between companies and politics. On this basis, frequent stakeholder meetings with a focus on the different expectations and problems should be organised and implemented.
- Establishing a partnership with producers and operators of hydrogen refuelling stations to build up a network for fast and easy refuelling. The “chicken and egg” problem has to be overcome as companies are waiting for the infrastructure in order to invest in fuel cell trucks.
- As fuel cell trucks are dependent on a sufficient network of refuelling stations this bottleneck can’t be solved in the mid-term. This problem has to be pushed and discussed on a higher administrative and political level as for an infrastructure roll-out planning security is needed. The project aims at demonstrating a zero-emission fuel cell-based solution within the Energy Model Region and has therefore the necessary justifications to actively push this forward.

6 Bibliography

- A. Ferrara and C. Hametner. *Impact of Energy Management Strategies on Hydrogen Consumption and Start-up/Shut-down Cycles in Fuel Cell-Ultracapacitor-Battery Vehicles* in IEEE Transactions on Vehicular Technology, DOI: 10.1109/TVT.2021.3127582.
- A. Ferrara and C. Hametner. *Rule-Based Energy Management Strategy of Fuel Cell/Ultracapacitor/Battery Vehicles: winner of the IEEE VTS Motor Vehicles Challenge 2020*. IEEE Vehicle Power and Propulsion Conference 2020, Gijon, Spain; Nov 18 – Dec 17, 2020.
- A. Ferrara, and C. Hametner. **Winner of the IEEE VTS Motor Vehicles Challenge 2020***: Energy Management of a Fuel Cell/Ultracapacitor/Battery HEV*.
- A. Ferrara, M. Okoli, S. Jakubek, and C. Hametner. *Energy Management of Heavy-Duty Fuel Cell Electric Vehicles: Model Predictive Control for Fuel Consumption and Lifetime Optimization*. IFAC World Congress 2020, Berlin, Germany; July 11–17 2020.
- A. Ferrara, S. Jakubek and C. Hametner. *Energy management of heavy-duty fuel cell vehicles in real-world driving scenarios: robust design of strategies to maximize the hydrogen economy and system lifetime.* Energy Conversion and Management, 2020. https://doi.org/10.1016/j.enconman.2020.113795
- A. Ferrara, S. Zendegan, C. Hametner, H. Koegeler, S. Gopi, M. Huber, J. Pell. *Calibration of adaptive EMS for fuel cell trucks*. AVL international simulation conference June 22-24, 2021.
- A. Ferrara, S. Zendegan, H. Koegeler, S. Gopi, M. Huber, J. Pell, C. Hametner. *Optimal Calibration of an Adaptive and Predictive Energy Management Strategy for Fuel Cell Electric Trucks.* Energies 2022, 15, 2394. https://doi.org/10.3390/en15072394
- Ferrara, and C. Hametner. **IEEE VPPC 2020 Best Paper Award** in recognition of the paper titled *Rule-Based Energy Management Strategy of Fuel Cell/Ultracapacitor/Battery Vehicles*: winner of the IEEE VTS Motor Vehicles Challenge 2020.
- Gerald Singer, Gregor Gappmayer, Marie Macherhammer, Patrick Pertl and Alexander Trattner. *A Development Toolchain for a pulsed Injector-Ejector Unit for PEM Fuel Cell Applications*. International Journal of Hydrogen Energy
- S. Zendegan, A. Ferrara, S. Jakubek and C. Hametner. *Predictive Battery State of Charge Reference Generation Using Basic Route Information for Optimal Energy Management of Heavy-Duty Fuel Cell Vehicles.* IEEE Transactions on Vehicular Technology, vol. 70, no. 12, pp. 12517-12528, Dec. 2021, DOI: 10.1109/TVT.2021.3121129.
- Second place in the **IEEE VTS MOTOR VEHICLES CHALLENGE 2021,** M. Dietl, A. Ferrara, and C. Hametner, *Energy Management of Dual-Motor All-Wheel Drive Electric Vehicle*.
- WIVA P&G. *Positionspapier: Vorschläge zur Änderung und Präzisierung des österreichischen Rechtsrahmens zu Wasserstoff und Power-to-X.* Jul 30, 2020.

7 Appendix

In the 3rd Zero Emission Call (FFG), a follow up project was summited. The project FC4HD - Heavy-duty fuel cell road demonstrator project – has the goal to develop and demonstrate a fully-fledged 40t zero-emission fuel cell truck (semitrailer tractor; 5-LH) for the first time worldwide. The FC4HD zero-emission truck and in particular its fuel cell system will fulfil the requirements of commercial vehicles regarding power, efficiency, reliability, and lifetime.
The project FC4HD multiplies and optimizes the "HyTruck" modular platform to a total fuel cell power of 310 kW by combining and upscaling "HyTruck" fuel cell systems with a power of 155 kW each and integrating them into the truck. The methodology (HW+SW) of a prototype FCCU developed in the project "HyTruck" will be used and the SW optimized in the FC4HD project for a combined fuel cell system operation (310 kW fuel cell system power). Furthermore, the control strategies and algorithm identified and developed in the "HyTruck" project will be optimized as well for a combined fuel cell system operation.

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