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Analysis of Alternative Fuel Technologies Impact on Heavy-Duty Vehicles Manufacturing Process

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1. Abstract

Current environmental situation requires reduction of all human activities that have heavy impacts on our planet. A considerable part of pollution comes from transportation, that produces about one fourth of total carbon dioxide, main source of greenhouse effect. This condition has required to switch vehicles fuels toward cleaner options as natural gas, electricity and hydrogen.

This paper aims to analyze which are the impacts of alternative fuel vehicles on the production process by examining four versions of a semi-truck. IVECO S-Way in its native diesel and optional natural gas versions have been modified in a joint venture effort with NIKOLA Motor Company in order to become a Battery Electric Vehicle and Fuel Cell Electric Vehicle. This project is called NIKOLA TRE and shares same mechanics and cabin with IVECO truck accompanied by obvious differences in propulsion system. As a starting point, manufacturing process of diesel version has been analyzed in order to spot differences with the one of natural gas vehicle. Main distinction is related to management and assembly of tanks, as well as vehicle testing procedure. Analogous study has been performed on electric and hydrogen variants by focusing on specific processes and components. Management of high voltage elements is the main issue of the BEV version since may have significant repercussions on safety of workers and final customers. For what concerns the process, main changes are present in assembly shop, where batteries, drivetrain and harness impose new requirements. FCEV production introduces serious differences with respect to other variants. Hydrogen is a hazardous substance that requires serious safety countermeasures during vehicle manufacturing. In particular, cabin manufacturing must be changed as well as the assembly and final testing processes.

The dissertation analyses implications on vehicle industrialization and proposes solutions to completely new challenges. In other terms, this work provides real guidelines to management of new technologies in production. In fact, it is clear that new propulsion systems impose many variations to processes, but do not generate any blocking issue.

2. Introduction

Transportation vehicles manufacturing process has changed and evolved in a dramatic way over time. Many new technologies have impacted the entire production of vehicles coming from new product features and innovative manufacturing practices. Topic of this paper is the impact of the alternative propulsive technologies over vehicle industrialization. Nowadays is crucial to sell a new generation of means of transport which eliminate or dramatically reduce environmental damage. Solutions lie in natural gas, electricity, and hydrogen as new fuels. This change leads to huge influence on new product development and also to industrialization. In this work, main focus will be posed to how these new vehicles can be mass produced, and, as a basis of analysis, heavy-duty trucks have been chosen.

Our environment is changing very much, and causes reside mainly in human activities. Main problematic phenomenon is the greenhouse effect which is substantially increasing atmospheric temperature leading to serious damages to the planet. It has been demonstrated the correlation of emissions of some gases and the severity of this process. Main influence is given by carbon dioxide which is significantly emitted by many human activities and has grown drastically in the last century. Transportation accounts for around 22% of its emissions principally due to combustion of fossil fuels. Since the gravity of the situation cannot be anymore underestimated, most government are imposing reductions in vehicle emissions until future complete abatements. Some solutions are present and are given by those which are called alternative fuel vehicles. These new technologies have already started reshaping the automotive industry and will continue their progress pushed by governments and people environmental awareness.

This work aims to analyze this new trend from the manufacturing engineering point of view. Alternative fuel technologies have significantly modified vehicles' characteristics and have introduced completely new components and subassemblies. Center of focus of this paper is however how these vehicles have to be produced, and which are the differences in the processes with respect to traditional diesel vehicle.

Car manufacturers are approaching a new full set of problems related to new vehicles, and solutions are usually not straightforward. Regulations are not always complete and exhaustive and so there is little support in defining practices. This is particularly true for hydrogen where completely new challenges are set, and insufficient guidelines are present. Same problem arises for battery electric vehicles even if in smaller terms.

For this reason, is clear the importance of this work which is in first place to understand new vehicles' production processes and then to provide a real-world example. Since all the production processes presented are real and effective, is possible to provide guidelines to new problems solving. With this paper is possible to have a clear idea of what is like to industrialize eco-friendly vehicles and to consider which are all the new issues.

Objectives of this thesis are to understand how alternative fuel vehicles are composed and which are their main components. Then, focus is switched to entire manufacturing process to underline differences with traditional vehicles. Finally, aim is to recognize which are all the problems and challenges in the plant and provide a series of effective solutions.

Paper starts with a general introduction of the environmental situation and of the main new technologies of propulsion systems. A reasoning is performed on infrastructure and fuels productions, assessing the real impact of new alternatives. First important point of the work is analyzed afterwards and is the explanation of selected vehicles. In particular, main focus is posed on new subsystems to understand main differences related to final products. In particular the IVECO S-

Way is considered in diesel and natural gas version, then the NIKOLA TRE in BEV and FCEV versions. Production processes of all the four variants are introduced and attention is placed on main differences. Emphasis is given to management of most important subsystems as for instance batteries and hydrogen tanks. Safety is quite important matter when dealing with high voltage and hazardous gas as hydrogen and natural gas. For this reason, all the aspects related to product and plant safety have been analyzed. Additional attention has been given to methodologies to improve new product industrialization. When a completely new and different product has to be produced, a way to reduce times and costs is to use World Class Manufacturing tools. In particular, importance has been given to Early Equipment Management and Process Failure Modes and Effect Analysis. With these tools is possible to improve industrialization process, preventing possible failures in production.

3. General considerations

3.1. The environmental context

Environment is changing, global temperature increase has been observed in the last century with heavy impacts on climate. Scientific evidence has widely proven the connection of this phenomenon with human activities mainly related to burning of fossil fuels. Greenhouse effect is at the base of this transformation. Earth surface should reflect sun rays back to space, but due to the presence of greenhouse gases in the atmosphere, some heat is absorbed, and rays are reflected again toward earth. These gases act as an insulating glass wall, and are carbon dioxide, nitrogen oxide, methane, and chlorofluorocarbons. This phenomenon leads to significant

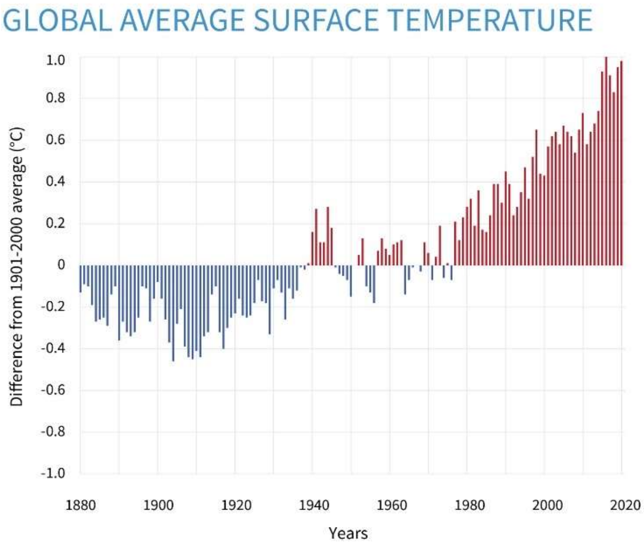


Figure 3.2 - Global Temperature Trend

increase in land and oceans temperature causing severe climate changes. Main impacts of this effect are on melting of glaciers and arctic sea ice due to sea

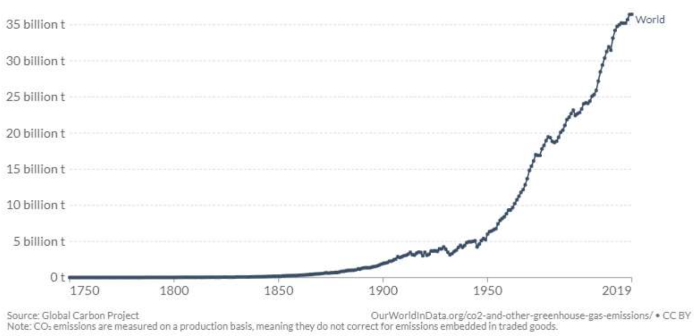


Figure 3.1 - CO2 Global Annual Emissions

temperature increase, as well as changes in rainfall pattern and air temperatures. Our planet has passed through temperature variations even without the presence of human life. But the fast increase in temperature contemporary with the increase of greenhouse gas emissions leaves no room for explanation as natural global behavior. In fact, natural variability or climatic influences as volcanoes, or sun, are not enough to explain the extent of this alteration. An increase of over 1°C has been measured and the speed at which is growing in unprecedented, with unknown future effects.

Glaciers cover around 10% of world landmass, if this amount of water is injected in the oceans a big sea level increase is resulted. Since 1993, an average of 3.1 millimeters per year of sea level increase has been measured. This phenomenon will be very harmful for countries or cities which are built at sea level. Millions of people may be forced to migrate considering that a large portion of population leaves by the sea. Impacts will also be on marine habitats and species, devastated by ocean temperature increase and acidification.

Extreme weather events are happening more frequently. Main are heatwaves, tropical cyclones, extreme rainfalls, droughts. In addition, fire risk has increased considerably, leading to further increase in CO2 emission and deforestation.

Future predictions show that greenhouse effect will continue to increase unless we highly reduce our GHG emissions. An increase of 0.2° C per decade is estimated with disastrous effects on our lives. Dry regions will get even dryer and there will be water shortage for millions of people. An obvious increase in strength of the effects shown before is expected.

This situation must change, it is necessary to reduce greenhouse gas emissions and slow the warming trend. In this direction is acting the European Union, by also setting fines for manufacturers who produce high emissions vehicles. This choice is changing all the automotive field toward a green future. EU directives have already placed a limit in CO_2 emissions of 95 g/km from 2020. This limit is achievable with small internal combustion engines or only with the aid of electrification. More stringent are future limits for next years. From 2025 maximum CO_2 emissions will be around 80 g/km, in 2030 will be of 60 g/km. With this kind of limits will be impossible for automakers to sell cars propelled exclusively by internal combustion engines. This regulation will oblige to produce Battery Electric Vehicles or highly electrified automobiles like plug-in hybrid. A further rule which is in discussion, is the total abatement of CO_2 emissions of vehicles in 2035. This choice would force entire automotive field to switch to electricity and hydrogen as fuels and to complete extinction of traditional cars.

3.2. The alternative propulsion systems

Today's very stringent CO2 emissions requirements are leading to a significant change in Automotive Field. Internal combustion engines, even if they have made giant strides in direction of lower environmental impact, cannot reduce anymore their CO2 emissions. This is because carbon dioxide is a direct result of combustion chemical process, and so cannot be reduced unless we significantly decrease amount of reactant. With fuel conversion efficiency increase, it would be possible to travel same distance by burning less fuel. This would reduce the CO2 g/km emissions very much. Today's most advanced technology enable to have efficiency of around 20% for gasoline and 40% for diesel engines. This kind of numbers lead to average g/km emissions of 151 for gasoline and 124 for diesel cars (average taken on Italian automotive fleet in 2016). Since from 2020 the EU limit is set for 95 CO2 g/km and in 2030 will be of 50 g/km, is very clear that technologically is not possible so far to avoid fines with internal combustion engine vehicles.

Alternative propulsion systems have taken the stage in response of technological limit. Most common propulsions systems are natural gas, hybrid, full electric and hydrogen.

3.2.1. Hybrid

There are many kinds of hybrid propulsion systems. In this paper, a focus will be on the most common one which is composed of combustion engine (mainly gasoline) and electric motor. Also, for this kind of system, there are many variants concerning parallel or series, or just regarding the amount of electric assistance that is given by motor. Principle behind hybrid vehicle is that it can use electricity to reduce fuel consumption and to recover energy that would be otherwise wasted. While a traditional vehicle is decelerating, kinetic energy is wasted in form of heat in the brakes. Hybrid cars can use their electric motors as generator and so transform that energy in electricity to be stored in a battery.

Main advantage of this technology is the reduced fuel consumption. Is possible to have drops of 8-20% with mild-hybrid and 20-45% with full hybrid vehicles. Another important benefit is reduced CO2 emission. With mild hybrid car is possible to have around 80-90 g/km and with full hybrid values of 40-60 g/km are possible. Concerning the user, an improved driving comfort and performance is guaranteed. Electric motor is well known to have high torque at low rpm, this effect adds to the low torque of gasoline engine to have a smoother torque distribution. In metropolitan zones, this kind of solution leads to big benefits.

3.2.2. Natural Gas

Natural gas vehicles are propelled by compressed natural gas (CNG) or liquefied natural gas (LNG) in an internal combustion engine. Fuel is composed by methane in gaseous or liquid state and other components as ethane, propane. Natural gas propulsion is widespread due to low emissions and running costs. Gasoline vehicles can be converted to burn methane, but same can be done with big heavy-duty diesel engines.

Natural gas can be used as compressed or liquefied. CNG is made of gaseous methane kept at pressures of 200-250 bar. For this reason, is necessary a specific metal or composite tank, but with this compression, gas occupies only about 1% of the volume that it has at atmospheric pressure. LNG is methane which is cooled so much that it changes state and becomes liquid. This transformation is done at atmospheric pressure to reach a temperature of -162°C. Volume from gas to liquid decrease up to 600 times with respect to atmospheric condition and so with the same tank volumes, is possible to considerably increase the vehicle range. LNG technology is used to transport methane all over the world and, in some cases, to power heavy-duty trucks. Difficulties are caused by the necessity of maintaining the LNG in liquid state. Special tanks with insulation are required, if the LNG temperature rises, methane starts to evaporate leading to a big volume increase. If the tank is not equipped with relief valve, there is the risk of reaching very high pressures. For all these reasons, liquefied methane must not be stored for long times and fits well a vehicle as a truck which travels every day. This explains why LNG is not used for passengers' cars.

For both technologies the refilling time is around 5-10 minutes and so it is comparable to traditional vehicles. A difference is related to safety; methane is highly flammable, escapes in the cabin may lead to serious risks for driver. Methane is a greenhouse gas; leaks are also pollutant and cause climate change. Advantages in term of environment are however very significant. CO2 emission is lowered by approximately one third with respect to traditional fuels, to about 94 g/km. Big decrease is however related to pollutants related to not-perfect combustion of traditional fuels. Being methane very clean, 75% less nitrogen oxides and 97% less particulate matter are produced. A further advantage comes if bio-methane is used. This gas is produced by organic waste gas releases and so from a renewable source, leading to big environmental advantage.

3.2.3. Electricity

Electricity is used for vehicle motion with a storage unit and a motor. Storage is usually done in a battery, which can be made of different materials. Most common used in automotive field is the Lithium-ion battery. This technology is the best available today in terms of energy density and longevity. Even if electricity is stored in DC, automotive electric motors are almost always run in three-phase AC. This is the reason why inverters are always present in electric cars since they oversee this crucial operation. The AC generated by inverter is obviously controlled by the driver with the accelerator pedal. From pedal input the alternator sets correct frequency and intensity of current to drive the motor. Alternate current is preferred in vehicular applications because AC motor can provide high power and efficiency characteristics. Most used technology is the three-phase AC induction motor, is composed mainly by a stator and a rotor, both of cylindrical form. Stator is made by windings that create electromagnetic induction to the rotor which is made of magnetic material. As all the electric motors do, this component can act also as generator if torque is applied on it. Energy retrieval is so possible in braking conditions leading to recover of significant power that would be lost as heat in brakes. In addition, electric motors have a torque distribution which is very high at low rpms and can rotate up to very high speeds. All these considerations demonstrate that the electric motor is for sure the best propulsion system for vehicles since does not need any gearbox or clutch and is able to recover energy in braking. The big problem arrives when we analyze storage of electricity in vehicle. Main issue is related to energy density that leads to bulky and heavy batteries which are not suited to small vehicles available volumes. Another problem is related to recharge times which are with best equipment around 2 hours or more. As introduced before, best technology adopted today for batteries is Li-ion. This accumulator is made of cathode (usually lithium cobalt oxide), an anode (graphite or lithium manganese oxide) and an organic electrolyte (usually ether). Principle of work is that lithium ions move from anode to cathode through electrolyte and release electric energy. Li-ion batteries are best batteries available and lead to many advantages, but some issues are related to safety. This kind of battery tends to overheat and catch fire and so must have cooling circuit that works every time. Main limiting issue is however related to energy density and cost. Battery has 100-265 Wh/kg that comparing to 12700 Wh/kg of gasoline lead to high weight disadvantage. Is important to state that from battery to wheel the efficiency is around 80% and for gasoline engines is only around 20%. Even considering that, electric vehicles need very heavy batteries with respect to full gasoline tank weight. In addition to weight disadvantage, Li-ion battery has volumetric energy density of 250-693 Wh/L, gasoline has 8760 Wh/L. This condition leads not only to heavy battery packs, but also very bulky.

Another important issue is related to environmental impact, BEV are spreading mainly due to fact that produce zero emissions. The problem is that the electricity by which are fed, is usually generated with fossil fuels. In USA, for example, only around 20% of electricity produced comes from renewable sources leading to high CO2 emissions of the BEV. In 2019, EU average share of energy from renewable

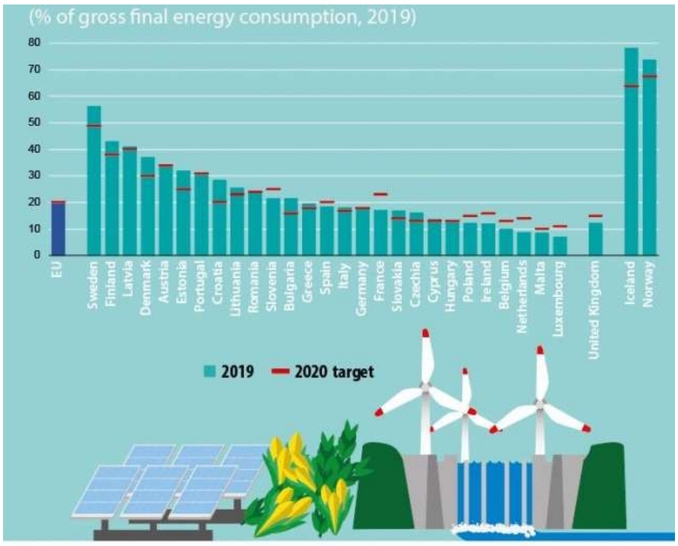


Figure 3.3 - Overall share of energy from renewable sources

sources was only about 20% and the average gCO2/kWh produced was around 300. Considering average of 0.196 kWh/km consumed by today's electric cars, we have an estimated 59 gCO2/km. For sure this data of emissions is much smaller with respect to what can be achieved with internal combustion engines (difficult to go below 100 gCO2/km) but cannot be said that in today's condition electric vehicles lead to zero emissions. One more issue comes directly from batteries. Lithium extraction is far from being a green process since requires big amounts of water, harms soils and causes air contaminations. Same thing happens for cobalt and nickel which also have big impacts. Finally, another problem arises concerning battery at the end of lifetime. Lithium cathodes recycling is very difficult and same happens for most part of batteries. This leads to big problems in battery at end of life since they must be carefully managed as they are very harmful for environment if some leakages occur.

Final consideration on Battery Electric Vehicles is that are very good in terms of propulsion but need to make many technological steps to have acceptable range and recharge times.

3.2.4. Hydrogen

Hydrogen can be used in vehicles in two ways: HICEV (Hydrogen Internal Combustion Engine Vehicle) where hydrogen is fuel in an engine, or FCEV (Fuel Cell Electric Vehicle) where hydrogen is used to produce electricity to run motor. Most used technology is the fuel cell, a device that can produce electricity from a pair of redox reactions. This device is similar to a battery since has cathode, anode, and

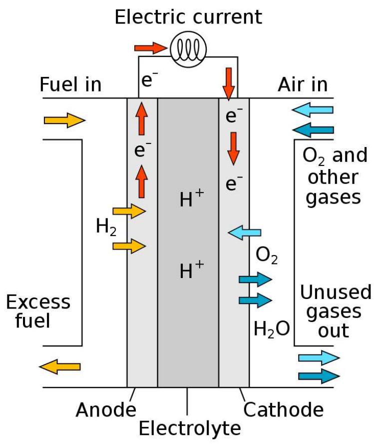


Figure 3.4 - Fuel Cell working scheme

electrolyte. Pure hydrogen H2 is introduced to the anode and oxygen O2 to the cathode. Protons travel through electrolyte membrane which is usually made of polymer. Because of this travel, electrons are forced to travel in the external circuit generating an electric current.

The only result of this process is creation of water, so FCEV leads to zero emissions.

Fuel cell must continue its operation and is not easy to stop and start every time. For vehicle applications this device is always coupled with a battery which is very small with respect to BEV but is big enough to provide transient performance and to store energy when vehicle is not in motion. This kind of vehicle is very similar to a battery electric vehicle but with addition of fuel cell and hydrogen tanks. Hydrogen is stored on vehicle usually at 350-700 bar, this gas is very flammable and so particular care must be placed on tank design. Today these tanks are built of carbon fiber due to its strength and lightweight. Main advantage with respect to battery is however range and refilling time. FCEV already present in the market are in fact able to travel distances of 500-800 km with a refueling time of around 5 minutes. Another advantage is that hydrogen has an energy density of around 34000 Wh/kg and so around three times the content of gasoline. This, in addition to high efficiency (like BEV, around 80%), leads to very high travelling ranges with low quantity of gas. In terms of volume, hydrogen has density of 2300 Wh/L and so about one fourth of gasoline. Therefore, hydrogen tanks are bigger in size with respect to gasoline tanks and this is the reason why hydrogen is compressed at high pressures. This comparison was made with the traditional vehicle since FCEV is considerably advantageous with respect to Battery EV. Hydrogen has in fact more than 100 times the energy density of Li-ion battery.

Hydrogen vehicle environmental impact is zero if we consider only the car, but for the fuel, there is the same problem of electricity which comes from fossil fuels. Hydrogen is in fact just an energy vector, hydrogen is generated from electricity or natural gas, and if the first does not come from renewable sources, inevitably the vehicle emissions will not be nil.

3.3. The infrastructure constraints and requirements

The alternative fuels proposed in this paper introduce serious advantages with respect to traditional fuels. There is however a big limit related to the fact that traditional fuel infrastructure has developed over many years and gas stations are present all over the world. Same thing cannot be said for alternative fuels infrastructure. This condition is an evident limit to the spread of new technological vehicles and could slow down the transition toward zero emissions.

Starting with natural gas, we must focus on first step which is its production. Main natural gas quantity was naturally produced very deep underground following an extremely long process. Remains of plants and animals built a thick layer on earth surface, this layer was covered overtime by sand and rock. These remains are full of carbon and hydrogen, under high pressure in millions of years they have been transformed into oil or into natural gas. Natural gas is in fact found today in cracks and spaces between earth layers. Through drilling is possible to create natural gas wells and extrapolate it. Immediately after, this gas must be processed for purification and compression for supply. Another possibility is related to bio-methane, which is made from renewable sources. Comes from biogas purification, this gas is generated through anaerobic digestion of agricultural waste, municipal waste and in general organic waste. Biogas is mainly composed by methane and so can be used to produce natural gas in a very green process. This gas is compressed, purified, and finally introduced in distribution. There are two main ways to transport natural gas, one is by methane pipelines and other is by tank wagons or tankers (ship). In first case is convenient to have transportation in form of CNG, and this is what it happens today for transportation to final customer's houses. The second scenario is used for long distances and LNG is preferred due to its considerably volume reduction. For what concerns automotive field, gas refueling stations are already present in some parts of the world. It is clear that it is not enough to have a switch from traditional fuels to natural gas. Must be said that concerning CNG the creation of a refueling station is quite simple due to only the connection to pipeline, same is for LNG that could be easily transported with tank wagons to stations as it happens with traditional fuels.

Concerning recharging of electric vehicles, a series of problems arises that is today not possible to be overcome. First problem is related to energy demand increase. Is possible to perform a simple calculation to estimate how much will be the energy demand increase in the following years if from 2035 only electric cars will be sold. If we consider average US data of 11.000 kWh/year consumed by each house and 13500 miles/year (around 22000 km/year) travelled by car, an average energy consumption of EV of around 0.346 kWh/mile and an average of 2 vehicles for each household, is possible to calculate energy consumption for adoption of BEV and domestic recharge. All this data are average US data based on references at the end of the paper. Finally, around 9000 kWh/year would be required for each household only to recharge the two possessed vehicles. This electricity demand is an increase of 81% with respect to today's average. This result shows that electricity production must be almost doubled in next decades if we really want to sustain transition toward zero emissions vehicles. A challenge is set, electricity demand increase will be difficult to be satisfied with increasing of renewable source percentage. A possible solution could be to adopt more nuclear power as source with all the difficulties that this implies. Renewable sources have the characteristic not to be continuous over time. Considering that electric vehicles would be mainly recharged at home during nighttime, this new demand peak could generate problems since during night solar and wind electricity production is almost zero. Infrastructure will require to be almost doubled if we consider previous calculations. Today's electric energy supply system is not enough to sustain such an increase in demand and huge investments would be needed to enhance and extend electric power grid. This would be enough if we just consider domestic recharge (up to 7 kW of charging power), if we include also recharging stations with high power (up to

250 kW), is clear that a serious upgrading of the electricity supply infrastructure is required.

Last considerations are done on hydrogen infrastructure. H2 can be formed with various methods. Most used are steam-methane reforming and electrolysis. First method is used to separate hydrogen from methane. This process is quite clean and produces small amount of carbon dioxide. Also, some carbon monoxide is produced but this can react in the water gas shift reaction to result in H2 and CO2. At the end, the carbon dioxide emissions for one kWh of hydrogen production are around 280 g. This value is amply smaller with respect to emissions related to electricity production with fossil fuels. Second method is to have hydrogen formed by electrolysis of water; DC current drives chemical reaction connected to two electrodes placed in the liquid. At the end, oxygen will appear at anode and hydrogen at the cathode. This kind of process is quite costly in energetic terms and so is less convenient than SMR. Must be said that if renewable energy source is only used, hydrogen produced will have zero carbon footprint.

Hydrogen production could be done in stations to use excess energy if low demand occurs. Grid balancing is very efficient and through electrolysis no wastes of energy are done. Most used method could be however off-site production. Hydrogen would be produced in plants with SMR or electrolysis and then delivered to refueling stations with tankers. This solution would require limited investments in adaptation of present stations and supply would be exactly as it is today for traditional fuels. Last alternative could be to have on site production. Refueling stations should be provided with electricity directly coming from renewable sources. This last option would be the most desired in term of costs and environmental impact, but as already said, electrolysis is not the most efficient method for hydrogen production.

4. Description of vehicles characteristics

In this chapter an introduction will be made on heavy duty vehicles used as reference for the paper. In order to highlight the specific differences in production for alternative fuel vehicles is in fact prior necessary to understand vehicles structures. Is important to comprehend which are the main systems and subassemblies present onboard so that is possible to explain specific care applied to each of them in the manufacturing process. This work is possible thanks to the fact that the vehicles analyzed on this paper are all based on the same chassis, cabin and mechanics. Is in fact true that many components are common to all four vehicles and are carry overs from IVECO S-WAY truck. This semi-truck has been taken as base to create a natural gas version called S-WAY NP that runs with both CNG and LNG. In addition, in a joint venture effort with NIKOLA Motor Company, this tractor has been modified to become BEV and FCEV under the name of NIKOLA TRE. Finally, all the four vehicles are very similar from aesthetic point of view even if their internal composition has many differences.

4.1. IVECO S-WAY characteristics

Figure 4.1 – IVECO S-WAY

IVECO S-WAY is a truck that has been designed mainly for European market. This vehicle can be configured in many different versions according to specific requirements. The main differences are between rigid and artic version. Rigid means that the trailer is mounted directly on same frame of the cabin. This kind of vehicle requires longer frame and usually have 6 wheels. For S-WAY rigid version is also possible to have 4 wheels, but, in any case, there are 2 traction wheels. Artic version is characterized by trailer completely separated from tractor. In *figure 5* can be seen a 4x2 version of the artic S-WAY, but also 6x2 version exists.

In general S-WAY 6x2 version can be 6.5 m long and 2.5 m wide. This version weights around 8500 kg. Main subsystems that compose the semi-truck are frame, engine, and cabin. As for almost all heavy-duty vehicles, diesel engine is adopted thanks to its high torque characteristic. In fact, the most powerful engine can provide 2500 Nm of torque and 570 HP. Automatic transmission is mounted with 12 gears and is connected by a driveshaft to the pair of traction wheels.

4.2. IVECO S-WAY NP characteristics

Figure 4.2 - IVECO S-WAY Natural Power

IVECO S-WAY NP is the version of the traditional semi-truck that is powered by natural gas. This vehicle can be refueled both with CNG (as passenger cars) and with LNG. Basing in fact on customer request, is possible to have either one of the two systems or also both, for maximum flexibility. As introduced in previous chapter,

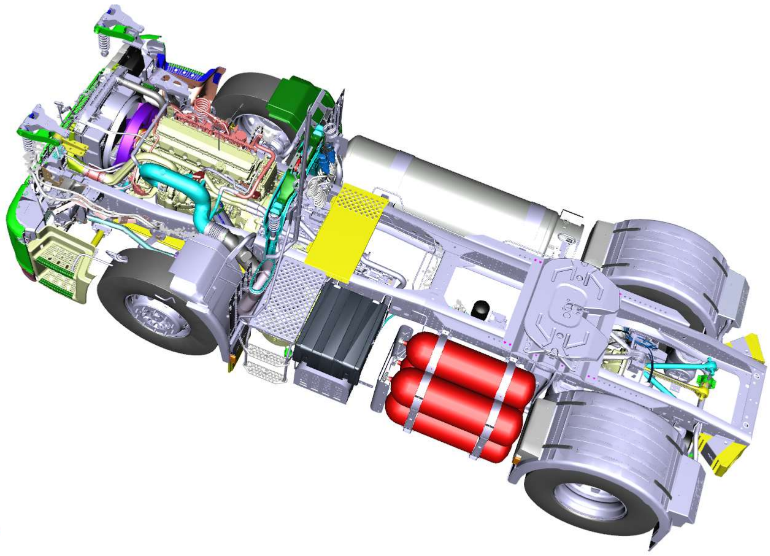


Figure 4.3 - S-WAY NP 4x2 CLNG

this technology gives many advantages; starting with CO2 emissions, is possible to have -95% if biomethane is used. Being combustion process very clean, is possible to have very reduced PM and NOx emissions. In addition, decrease of total running costs is significant due to the quite lower fuel cost. Noise reduction is resulted from the vehicle and advantages are not over, being LNG very energy dense, this truck is able to travel distances of 1600 km with the biggest available tanks. Is in fact possible to install different tanks in many distinct positions of the chassis. LNG tanks can be of four dimensions (up to 540 L) and can be installed on the sides of the frame; concerning CNG, is possible to have tanks on the sides and on top of the frame. In addition is also possible to have them behind the cabin.

S-WAY NP is powered by converted CURSOR diesel engines to burn natural gas. Most powerful version produces 2000 Nm of torque and 460 CV from 12.9-liter engine.

Main differences with respect to diesel vehicle are tank positions and dimensions. There are in fact different gas and heating pipes specific for natural gas. Another difference is found in the exhaust since no SCR is necessary and so no urea is used. In substitution is present a TWC converter that occupies less space.

From this product introduction is possible to state that NP version gives significant advantages with limited variations from traditional vehicle. So, also from what concerns manufacturing process, will be possible to see that differences are small and not complicated, giving this product great advantages.

4.3. NIKOLA TRE BEV characteristics

Figure 4.4 - NIKOLA TRE Battery Electric Vehicle

NIKOLA TRE BEV is a full electric semi-truck based on IVECO S-WAY platform. It has been developed in the joint venture work of the two companies. This truck has remarkable performances and will lead the way toward electrification of heavy-duty vehicles. For the customer, main advantages lie in fact in driving performances. This Semi has 480 kW of continuous power output and 1800 Nm of peak torque. TRE BEV is so capable of 121 kph max speed and 17% grade start at full load. This data, combined with the fact that truck does not need any gearbox, leads to a continuous acceleration with absence of emissions and any noise. Batteries are grouped in 9 packs that work at 800 V with around 80 kWh capacity each. The total energy is so around 753 kWh and provides a range up to 550 km at full 40 tons load. Charging can be done with up to 350 kW chargers and has an average time of 120 min. Vehicle weight depends on the version, 6x2 version weights around 15 tons and so around one third more than the traditional S-WAY.

This vehicle has been designed for metro-regional applications. It means that fits medium haul point to point delivery with moderate speeds and frequent stops.

NIKOLA TRE shares many components and systems with traditional diesel vehicle. Chassis is very similar with differences in crossmembers and brackets. Front axle remains almost the same as steering system, with the difference of having an electric pump to drive it. Cabin is the identical with small interior and exterior variations, its suspensions and tilting system are the same. Pneumatic system which acts the brakes is almost equal, the big change lies in the fact that air compressor is electric and not driven by an engine. This system drives brake cylinders as in all heavy-duty trucks. Another structure which works with air is the air suspension. Air bags are placed at the rear to have upward and downward movement of the fifth wheel to attach or detach the trailer. Low voltage system and harness are the same of the diesel truck. All the other structures present on board have significant differences:

- Battery pack:

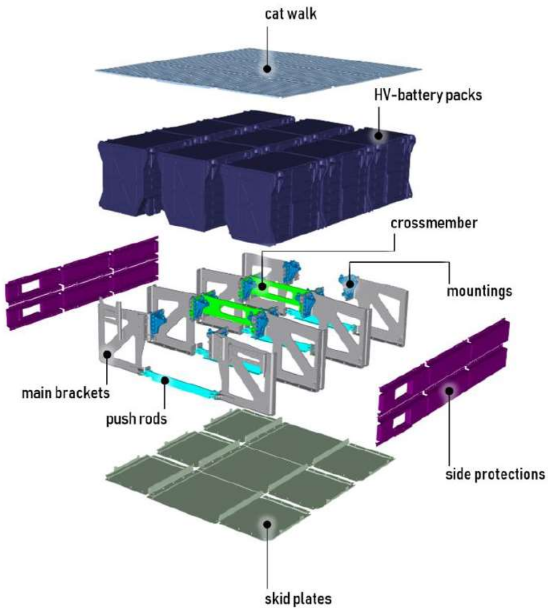
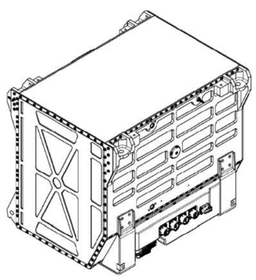


Figure 4.5 - NIKOLA TRE BEV Battery pack assembly

This electric truck features 9 high voltage batteries. Each battery pack has specifications showed in *table 1*, weights around 500 kg each and contains 8 cells.



Performance Data						
Module Configuration Within Pack	Series	8	Parallel	1		
Voltage [Vdc]	Nominal	689.7	Maximum	806.4	Minimum	480.0
Voltage, operating [Vdc]			Maximum	796.8	Minimum	576.0
BOL Capacity, [Ah]	Total	115.2	Usable	103.68	EOL	92.16
BOL Energy, [kWh]	Total	80	Usable	72		
Max Rated Continuous Charge, [A]	Continuous	103.68 [0.9C]				
Max Rated Continuous Discharge, [A]	Continuous	172.8 [1.5C]				
Max Rated Pulse Discharge, [A]	10s	460.8 [4.0C]				
BOL DCIR, [mΩ]	30% SOC	≤ 240.0				
Cell Temperature Limits						
Charge [°C]	Minimum	0	Maximum	50		
Discharge [°C]	Minimum	-20	Maximum	60		

Table 4.1 - Battery Pack Specifications

Battery packs are installed between cabin and rear wheels. With sustaining brackets, three batteries are placed on each frame side and three in the center of the frame, between the side members. Skid plates and side protection are assembled to protect batteries, HV harness and cooling pipes from the external. On top of the pack there is a catwalk that allows to stand on the truck.

- Rear axle:

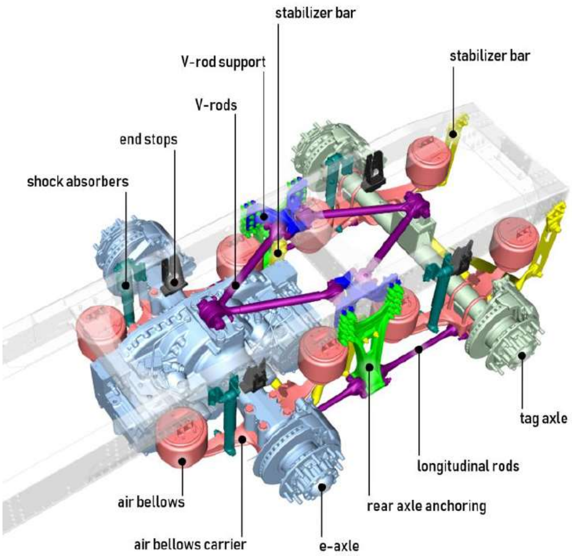


Figure 4.6 - NIKOLA TRE BEV Rear Axle

Rear axle is very different with respect to traditional semi-trucks. Suspensions and shock absorbers are the same, but the main variation is connected to the e-axle. This axle is composed by two alternate current electric motors that together can provide up to 480 kW of power. These two motors work as generator in decelerating situations to be able to recover the kinetic energy that would be otherwise lost.

- Thermal management system:

Thermal management system is specific to electric vehicles. In NIKOLA TRE this system is divided in three main parts. First one is related to cabin cooling and heating. This is done with a specific water pump, condenser, heater, and HVAC. Cabin cooling is however just small system with respect to the others which have the role of cooling batteries and motors. As already introduced, Lithium-ion batteries are very dangerous if overheated. This is obviously influenced by external temperature and may happen when big amount of energy is exchanged.

HV battery cooling/heating system works to maintain batteries between acceptable temperature limits. All the system is placed in the front of the vehicle,

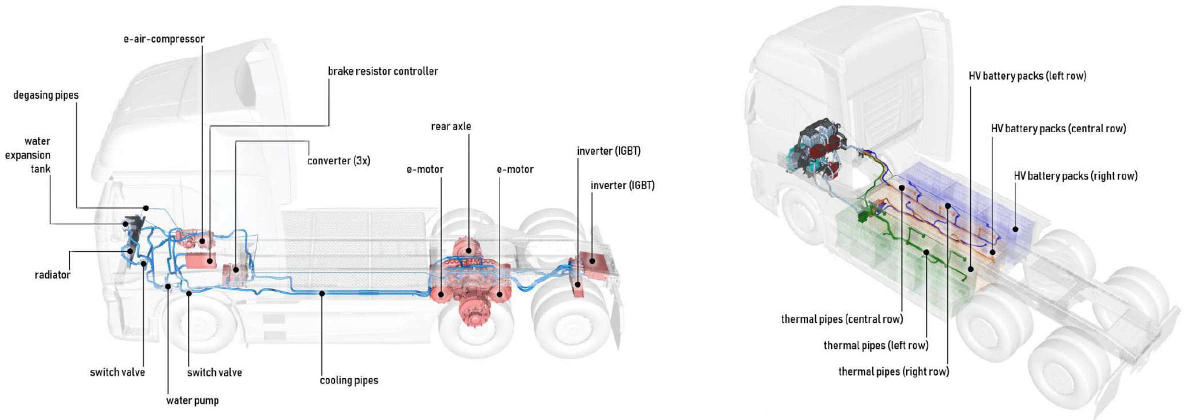


Figure 4.7 - NIKOLA TRE BEV Cooling Systems

and it is composed mainly by radiator, water pump, water heater and condenser. From these devices starts the piping to reach each battery, which is designed to have an internal circulation to allow cooling of each of the 8 cells present inside each pack. It is clearly a closed circuit and so cool water that goes to the batteries returns through hot water pipe. Third system is present to cool the motor and HV auxiliaries. It is composed by similar components of the previous two and is similarly placed in front of the vehicle. Pipes are quite long since they must reach the e-axle and the inverters placed at the back of the truck.

- High Voltage electric system:

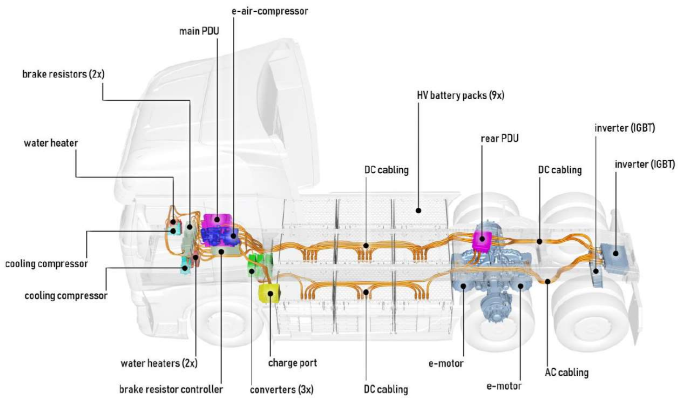


Figure 4.8 - NIKOLA TRE BEV HV electric system

High voltage system is mainly composed by converters, inverters, harness, and charge port. Converters are able to change DC voltage while inverters have the crucial role to transform DC into AC. With this operation all the characteristic of alternate current are set and so the e-motors are driven. Until the inverter, harness is passed just by direct current. Connection of inverter to e-motors is however done by alternate current cables.

NIKOLA TRE BEV is produced in two versions: 4x2 is made for EU market and 6x2 mainly for US market.

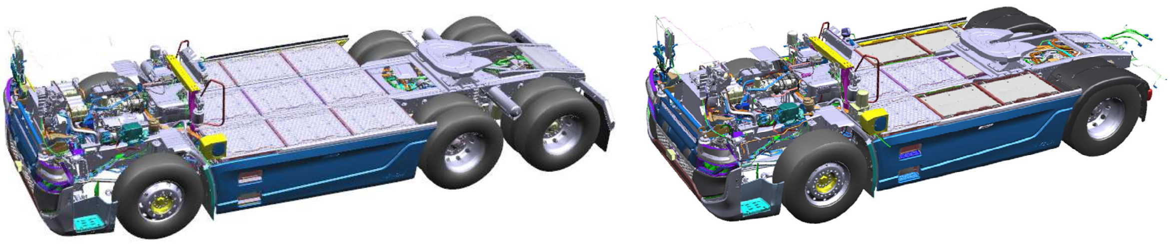


Figure 4.9 - NIKOLA TRE BEV 6x2 and 4x2 versions

Main differences of the two versions lie on the back. US version's chassis is obviously longer to accommodate more wheels and rear suspensions. For what concerns e-axle there are no big differences since traction wheels remain the same. Battery pack is exactly the same and identical are the thermal systems. All the electric systems of the vehicle are equivalent including inverters, dc-dc converter, and CPUs.

4.4. NIKOLA TRE FCEV characteristics

Figure 4.10 - NIKOLA TRE FCEV

NIKOLA TRE is also designed in a version with fuel cell to have hydrogen as energy source. This vehicle solves some of the issues and limits of the BEV version. Being hydrogen very energy dense, is clear that long ranges are possible with tanks that contain limited weight of gas.

BEV			FCEV
MUNICIPAL	URBAN DELIVERY	REGIONAL DELIVERY	LONG HAUL
Rigid 4x2 / 6x2 (6x2Y/PS) <100 mile	Rigid / Artic 4x2 / 6x2 (6x2Y/PS) / 6x4 50-300 miles	Artic 4x2 / 6x2 / 6x4 200-500 miles	Artic 6x4 500-800 miles

Table 4.2 - NIKOLA TRE Project Range Mission

It is possible to see that FCEV is targeted to long haul travel that would not be possible with just batteries. In addition to this advantage, average refueling time is just around 15 min. This is a game changer since the BEV version needs 120 min to recharge half the range of the FCEV. These two combined advantages suggest that this kind of vehicle is the real alternative to traditional trucks.

NIKOLA TRE FCEV is based on its full electric “brother”; chassis, cabin and powertrain are the same and so are the driving performances. This hydrogen truck needs however to have batteries in order to recover energy in braking and to provide max transient performance. For this reason, one battery pack is installed in the frame between side members. Mechanical parts related to suspensions and trailer interface are the same. Cabin is equal but with the difference of having covers for hydrogen tanks. These covers act also as aerodynamic enhancers. Concerning cooling system, HVAC, battery, and motors cooling are still present. The only difference is the addition of the fuel cell in the system. Another minor difference is in weight, 6x2 version weights around 13 tons, so slightly less than the BEV version. Due to the heaviness of batteries, it would be expected to have Bev heavier than FCEV. This is not the case since hydrogen tanks are very heavy in order to sustain very high pressure and each of them has a thick metal protection cage.

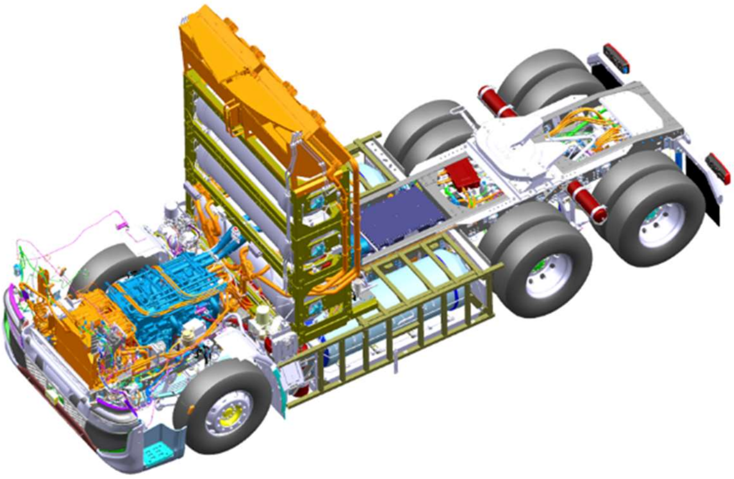


Figure 4.11 - NIKOLA TRE FCEV Architecture

Main differences with respect to BEV are:

- Fuel Cell:

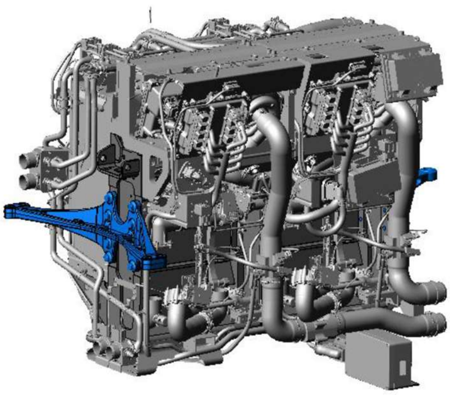


Figure 4.12 - Fuel Cell

Fuel cell is the device which can transform pure hydrogen into water by generating electrical energy. This device is fed with pure hydrogen from the tanks and highly filtered oxygen taken from the outside. Fuel cell is quite bulky and is in fact placed in a low position between side members of the frame. It obviously requires HV connection as well as cooling loop connection.

This particular fuel cell is able to supply 300 kW of power and so is not enough to provide max power required by motors (480 kW).

Another difference of this system is related to the fact that has an exhaust like traditional vehicles. From the fuel cell however exits only water that is released in the ambient with two pipes.

- Hydrogen system:

Hydrogen tanks mounted on NIKOLA TRE FCEV are 5. Two are mounted at the sides of the HV batteries and three right behind the cabin.

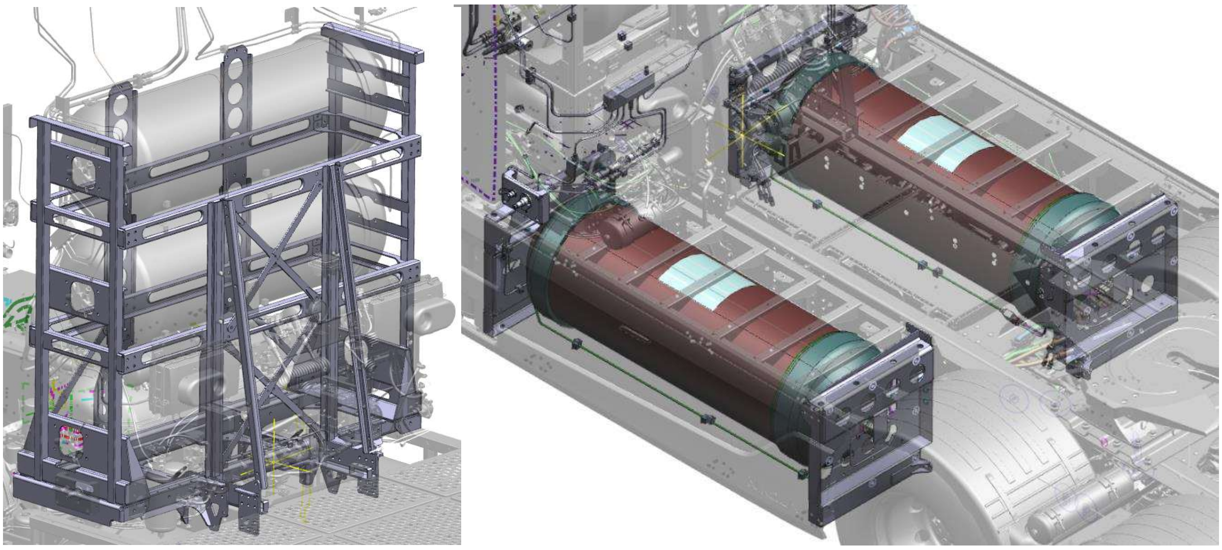


Figure 4.13 - NIKOLA TRE FCEV Hydrogen Tanks

These tanks are filled with H_2 up to 700 bar of pressure and in total can store up to 13 kg of hydrogen each. Since hydrogen is highly explosive, safety aspect is very important. In terms of crash resistance is critical that side impacts do not bump into the tanks and for this reason strong metal structures are placed around each one of them. Further safety issue is related to cabin that must be completely hermetic. Risk is that some hydrogen could leak into the cabin and could lead to fire. Hydrogen is very light and tends to go upward, it could collect at cabin roof and with a spark could explode. For this reason, all the cabin holes and joints must be closed. In addition, a sensor must be placed in the cabin to sense if there is some H2. Sensors are anyway installed in many valves of the hydrogen system so that leaks can be found immediately. Flammability limit of hydrogen with air is around 4%, if the sensor finds values which are even close to this value is crucial to have a vehicle alarm and stopping procedure. In this way the driver can escape from the cabin and ventilation may expel as much hydrogen as possible. H2 system is divided in two main circuits which can be detached by valves. Tanks and piping to the Fuel Cell compose a first circuit and the FC alone has its own circuit. The entire system apart from the tanks works at around 15 bars.

In case of accidents or fire around the vehicle, sensors are able to understand the situation and expel all the hydrogen present in tanks from the top of the truck. This controlled ejection of gas avoids tank explosion which could create huge damages to environment around the truck.

- High voltage electric system:

High voltage system has some differences with respect to BEV, fuel cell is obviously connected to the HV harness and is placed where converters were positioned in BEV. Just two batteries are installed, and inverters are in the same position.

5. Diesel vehicle manufacturing process

Traditional fuel heavy-duty vehicle manufacturing process can be simplified in few big steps:

- Body shop: the first phase starts with metal plates which are pressed and welded together in order to produce the cabin. Chassis is produced with stamping and bolting of side members with cross members. For some joining riveting can also be used.
- Painting: cabin passes in the painting line where it is immersed in dipping tanks so that a corrosion resistance layer is applied on all surfaces. Then color paint is applied and cured in ovens. In the same process is also added some sealant foam that avoids water infiltrations and vibrations.
- Assembly: chassis arrives upside down to the beginning of assembly line and in first stations is assembled with supports and brackets. Then suspensions are mounted, and it is rotated in final vehicle position. Some other components are mounted as well as the engine. Then cabin marriage with the frame is done and all connections are fitted. Cab arrives from a specific trimming line which starts from painted empty cabin and installs all the interior trim. After marriage the various circuits are filled, wheels are mounted, and last aesthetic trims are assembled. Finally, EOL testing is performed, and the vehicle can be delivered to customer.

These steps are common in the entire automotive field, what is different for heavy-duty vehicles is the reduced number of components. These parts have however high weights, which requires assistance of lifting tools in almost all assembly processes. Now a quick introduction on the IVECO truck production process will be made just explaining principal phases.

S-WAY is produced starting with assembly of the chassis. Frame is composed of two side-members joined to various crossmembers. This operation is done both by riveting and bolting. The chassis is drilled in order to have many holes that will be used in next processes to assemble brackets and supports for components. Chassis is the first part on which everything is mounted and so it is inserted at beginning of the assembly line.

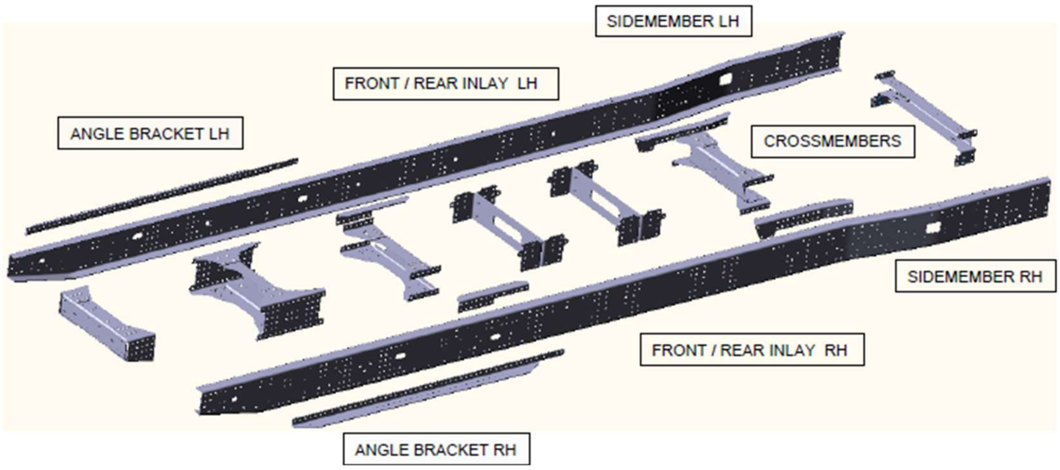


Figure 5.1 - IVECO S-WAY Chassis

In first workstations the frame is positioned on moving AGVs (Automated Guided Vehicle) that will move it through all the production line. The chassis is positioned upside down to simplify the assembly of many components at beginning. In following workstations, it is enriched of various supports; main ones are for suspensions, exhaust, engine, and gearbox. Other supports are assembled for wiring and piping all over the vehicle. In next stations the FUP (Front Underrun Protection) is mounted, this component is crucial to avoid small vehicles to go under the semi-truck in accidents. Then the pneumatic system is mounted with its piping, pump, and air tanks. Belonging to the same system are the pneumatic suspensions, are assembled for the cabin and for the truck's rear. After all the electrical wiring is laid down and locked in supports, the suspensions sub-assemblies are mounted. These sub-assemblies have to be prepared in production isles close to main production line and moved on the vehicle with help of lifting crane. Differently from rear suspensions, front ones are not pneumatic, they work with leaf spring and torsion bars. Last operations with upside down frame are mounting of propeller shaft and exhaust system. Then rotation is performed with two special cranes which lift the chassis from the two ends of the side-members,

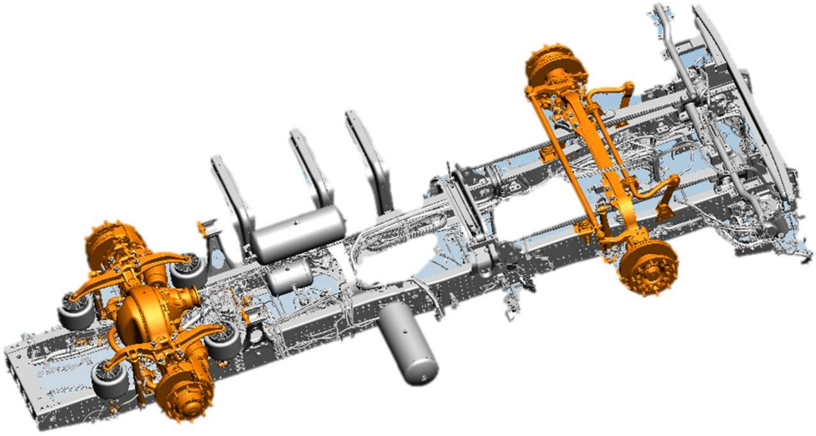


Figure 5.2 - S-WAY Suspensions Assembly

they rotate it and lower it on AGV. Main following operation is the engine marriage. Engine arrives as sub-assembly with its gearbox and is lifted and mounted on the chassis. Here all connections are performed, engine is mechanically fixed to vehicle and all the wires and pipes are coupled. Then radiators and cooling systems are assembled prior the cabin marriage.

Cabin arrives already trimmed from another line. Cabin manufacturing starts with stamping of metal and welding. Then it goes through all the painting process which is made of dipping tanks for corrosion protections and sealant application. In

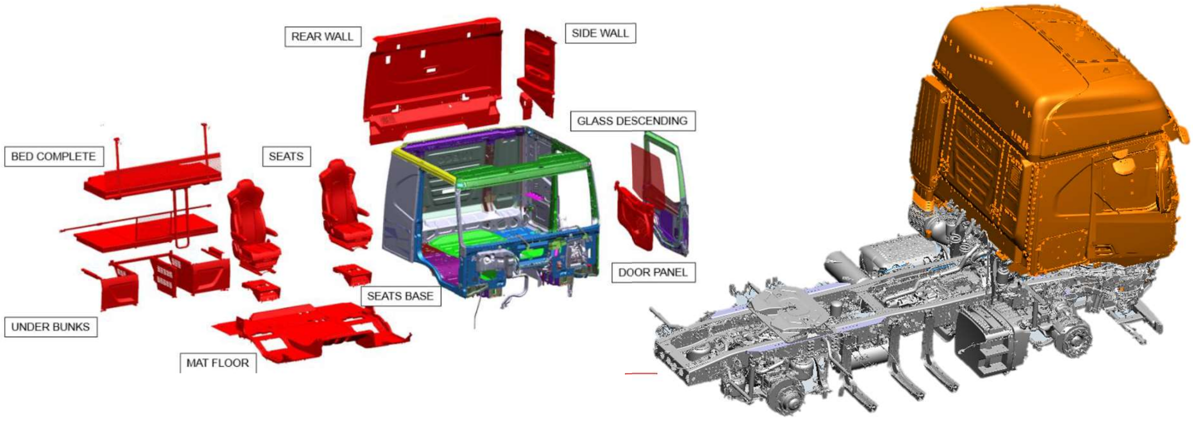


Figure 5.3 - Cabin Trimming and Marriage

successive steps the cabin is painted with several layers and finally cured in oven. Cab is then trimmed with all the interiors components as the dashboard, seats, roof, windscreen and others. Then cabin is shipped to S-WAY assembly line where it is lifted and married with chassis. Then it obviously fixed and all connections are performed. In following workstations exterior trims and fuel tank are assembled. Last missing operations are filling of all the liquids and assembly of wheels.

All the vehicles which go out from the assembly line must be tested in order to be delivered to customer. First step is the functional test, vehicle is checked to see if every system works properly. In particular, all the commands of the dashboard are tested. Next test is conducted with vehicle entering a water cabin where heavy rain is simulated. There are many sprinklers which throw water from roof and sides, at the end the cabin interiors are checked in search of every possible infiltration. Vehicle is moved to next step which is the dynamic roller test. Truck is placed on rollers and driven following a specific cycle. With this check, is possible to understand if everything concerning propulsion works in a proper way. Then brake test is performed. Vehicle is placed on rollers that in this case are motored. Wheels are accelerated with rollers and then the driver brakes. Braking torque is measured and compared with thresholds. Headlamps are checked as well as the wheel alignment in a specific station. Now final assemblies are done on exterior trim as side skirts and aero kit. Finally, last step before shipping of the vehicle is the weighting. This final test is performed to assess if every component has been mounted.

6. Natural Gas vehicle manufacturing process

6.1. Manufacturing Process

Manufacturing process related to natural gas vehicle remains almost the same comparing to the diesel version. The reason lies in the fact that there is just slight difference between the two products since they share same chassis, cabin, and drivetrain. This is not completely true since the engine has modifications as well as the gearbox. But can be said that many components of the subsystem are shared. For this reason, in plant based in Madrid, the two vehicles are produced on the same line. On production line the operations are same with different assemblies in some specific workstations. This is the reason why in this chapter, focus will only be on the main differences between the final assembly processes. Since this vehicle is produced in many variants as with only CNG or only LNG or with both systems, CLNG version manufacturing process will be analyzed so that is possible to understand all the differences related to the two systems.

Final assembly starts with chassis on AGVs. The frame is the same of the diesel version but in the first workstations is enriched with slightly different supports and brackets. Some specific systems are mounted as the fuel pipes between left and right side-member. Since natural gas is a much cleaner fuel, a different exhaust system is mounted and does not require urea for post oxidation. So, at this point of the process, some specific brackets are mounted to sustain new exhaust. Another enrichment is with the heating pipes which have to reach tanks which will be mounted on side of frame. In next stations pneumatic pipes and electrical harness are mounted. Fuel tank supports are assembled on the sides of the frame and are clearly different for CNG or LNG. The reason is that LNG is stored at low pressure in a big single tank. CNG is stored at high pressure in multiple tanks which compose a subassembly. So, for compressed gas, supports are just an interface of the subassembly cage with the frame, for the liquified gas they are direct interface of the tank with the chassis. Suspensions are assembled on the frame and then everything is rotated, and engine marriage occurs. Must be underlined that engine is very similar to diesel version so every operation remains unchanged. Propulsion system is prepared in a small parallel line which ends at the marriage workstation. Next passage is when CNG tanks are mounted to the frame. Tanks are assembled to compose a subassembly. After they have been tested, they are mounted with

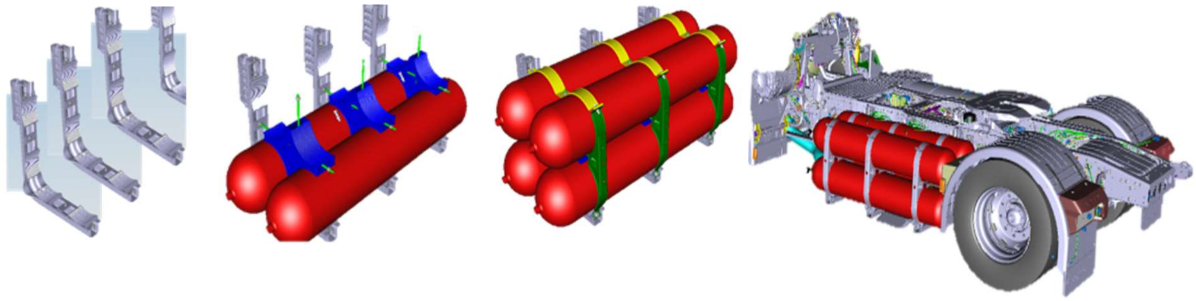


Figure 6.1 - CNG tanks assembly

valves and pipes and then joined together in groups of four. Tanks are kept together with metal supports and the last ones create interface with the chassis. In next workstations all the unions with fuel pipes and engine are performed prior the cab marriage. Then, tanks are enclosed with a metal cover to ensure protection. Last steps in the process are the assembly and connection of LNG tank. Fuel pipes are

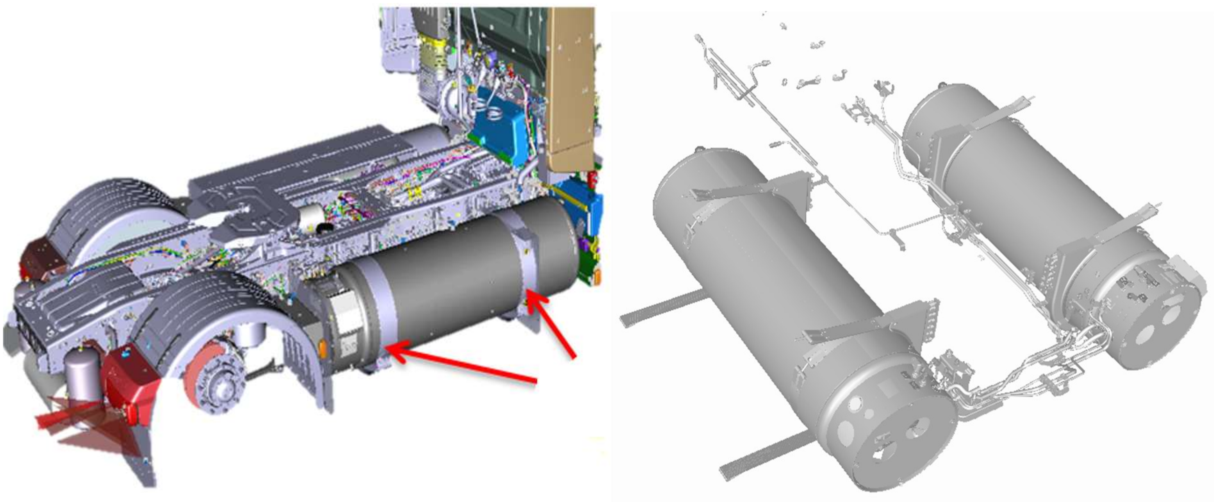


Figure 6.2 - LNG tank assembly

all connected, and no covers are placed to protect it. That is due to the fact that pressures inside this tank are quite low, and no explosion risk is present. Being this one the last process, vehicle is then moved to functional area where some tests are performed. Tanks are filled with small amount of CNG to reduce any risk in assembly process. For this reason, the vehicle has to drive directly to the gas station where every tank is filled with CNG. For the testing process also LNG tanks are filled with CNG. First tests on vehicle are done by filling the circuit with high pressure nitrogen. This gas leads to limited risk and so can be performed also indoor. High pressure is reached in the system and then the vehicle is left resting. At the end the pressure decrease is measured. Further tests are performed on the vehicle fuel system. Tanks are tested extensively before their assembly on vehicle so do not require any further check. When vehicle high pressure system is tested, all tanks have in fact to be completely closed. Test is made by filling the circuit at 200 bar for CNG and 14 bar for LNG. Vehicle is then left waiting for some time while a gas detector is used to sniff any leak. This device is able to find any kind of leak, even if very small. Sniffer has to be positioned on all connections of the system, in particular on pipes and valves. If leaks are detected, the test is stopped and assembly torques are checked. If rework was successful, the test is performed again. Acceptance criteria is below 15 cm^3/h of leakage. Another test is performed with soap and water and is placed on the system. With this simple test is possible to see bubbles that signal each leak.

At the end of this preliminary tests is sure that all the high-pressure system does not have any kind of problem and so usual testing procedure is performed. First checks are done on functionalities, each button must perform its operation. Vehicle is then assessed for performances in accelerating and braking, and also is put in water cabin to see any internal infiltration. Wheel alignment is checked with specific sensors and adjusted by an operator acting on the suspensions. Headlamps are calibrated and same occurs for ADAS radars. At this point the vehicle is ready to be delivered and the assembly process is finished.

6.2. Management of Tanks

Management of CNG components is regulated by UN/ECE-R110. This law classifies all the components which compose the system apart from containers. There are 5 classes to which every part is organized based on working pressure, starting from 20 kPa to 26000 kPa. For each of these classes some specific tests are mandatory in order to have part approval.

Concerning CNG containers they are divided in 4 types:

- Type 1. Made of metal. Usually made of steel, is the most common. It has no protection, just paint.
- Type 2. Metal liner reinforced with resin; hoop wrapped. Partial wrapping is made of glass or carbon, or polyester resin.
- Type 3. Metal liner reinforced with resin; fully wrapped.
- Type 4. Resin impregnated continuous filament with non-metallic liner (all composite).

In order to get approval, containers must also undergo a series of tests. If approval is received, a marking plate must be attached to the tank with serial number, capacity, CNG marking, operating pressure, mass.

Tanks arrive to the plant already tested and approved by the supplier. This component does not require any particular care since it arrives without high pressure gas. Is only important to avoid any damaging of the tank that could impact safety of operators and also of final customer. First operation performed in plant is the visual inspection. Any also minimal crack could lead to leaks and possible hazards. On this vehicle are mounted type 4 tanks. They arrive without the interface with the system and so next operation is to join valves to containers. This step is performed in subassembly area and is done with particular care for safety reasons. Correct torque must be applied to valves in order to avoid any possible leakage. To be sure, a leakage test is always performed after this operation. The tank is filled with a mixture of N2/H2 or directly CNG, with a particular machine every leak is inspected. Sniffer device is able to sense every small leak that is usually coming from valve interface. This gas is not wasted but reused every time. Then the CNG tanks are assembled together in packs of four and piping is connected. After that is possible to install on vehicle.

For what concerns LNG tanks, the problem is less challenging. The reason is that liquefied natural gas is kept at low pressure due to its highly increased density. Liquefaction is obtained with cooling at -162°C and pressure is usually around 7-15 bar. For this reason, LNG tanks are tested as CNG ones but with pressure of around 15 bar. Leaks are inspected with sniffer. For tank performance is crucial that it is very much insulated as it has to act similarly to a thermos in order to keep the gas cool. After being tested, valves are assembled and tank can go directly at the assembly workstation.

6.3. Safety Considerations

Natural gas is one of the safest transport fuels available. It is naturally odorless but is always odorized in order to be detectable very soon in case of leaks. Smell of gas can be detected at concentrations of around 0.3% and so well before the lower flammability limit. Combustion limits are in fact between 5% and 15%. It is clear that if a leak occurs fire can be prevented, even because being at high pressure in tanks, a leak is always accompanied by hearable noise. A further characteristic of natural gas is its lower weight with respect to air. This gas tends in fact to go up and to dissipate into the atmosphere. For this reason, if a leak is present outdoor there are no safety issues. Only problem would be related to the fact that methane is a greenhouse gas and have terrible effect on environment.

Natural gas is not known for possible toxic or poisonous effects. Exposure may result into symptoms similar to those ones caused by oxygen deprivation. But since it has strong odor, is quite unlikely that this would occur. This is the reason why in the production environment not particular attention must be taken on the natural gas apart from fire risk. Since it goes up, when the vehicle is indoor, there is risk of gas accumulating under the plant roof or under vehicle's roof. With a spark or an electric fault this condition may lead to big explosion. For this reason, is always crucial to have working ventilation system and gas sensors placed under the roof.

For what concerns LNG, has similar hazards with respect to compressed gas but since it is at very low temperature may involve state changes in leakage situation. If spilled in environment, sudden temperature increase will cause its immediate boiling which result in a highly flammable vapor cloud. The problem is that this cloud tends to require more time to reach ambient temperature and to dissipate in the atmosphere. Another risk is cryogenic burns to the skin if someone gets close to LNG leak.

Safety of the plant is ensured by a simple and very effective measure which is the filling of tanks at the latest moment possible. With this trick is possible to avoid any of the risks stated before and do only testing and reworking operations with gas onboard. A further safety solution would also be to perform the reworking operations outside the building.

7. BEV vehicle manufacturing process

This section analyzes the manufacturing process of an electric heavy-duty vehicle. A first introduction of the main passages that compose the manufacturing process is done focusing the attention on processes which are specific to electric vehicles. Main differences are in fact analyzed to understand which is the additional manufacturing effort required to produce this kind of new vehicles. Main impact on processes and facilities will be examined and will be mainly on the vehicle assembly process. Many new components have to be mounted on the vehicle and each of them requires particular care.

Furthermore, high voltage items require attention even in other steps of the process prior the final assembly. Main focus will be on battery management since it is the component which must be treated with most care for safety reasons. Finally, all the risks and countermeasures present in the BEV production process are considered.

7.1. Manufacturing process

Manufacturing process of an electric heavy-duty truck has some differences with respect to traditional fuel vehicle. First considerations are related to high voltage systems which require specific care during installation. This section will introduce the entire manufacturing process by focusing on those phases which are specific to the electric version. An overview is done on the entire process in order to compare it with diesel version even if production volumes of the two plants are very different. For what concerns ULM plant for BEV, takt time is around 90 min and so it is a very low productivity. Concerning diesel vehicle, manufactured in MADRID plant, takt time is around 6 min. For this reason, is crucial to underline that a direct comparison cannot be made between the two production processes. Focus will be for this reason on specific assembly operations and not on the comparison of the two production lines.

As it happens for traditional trucks, manufacturing process starts with chassis which is assembled and arrives to the start of the assembly line. The production

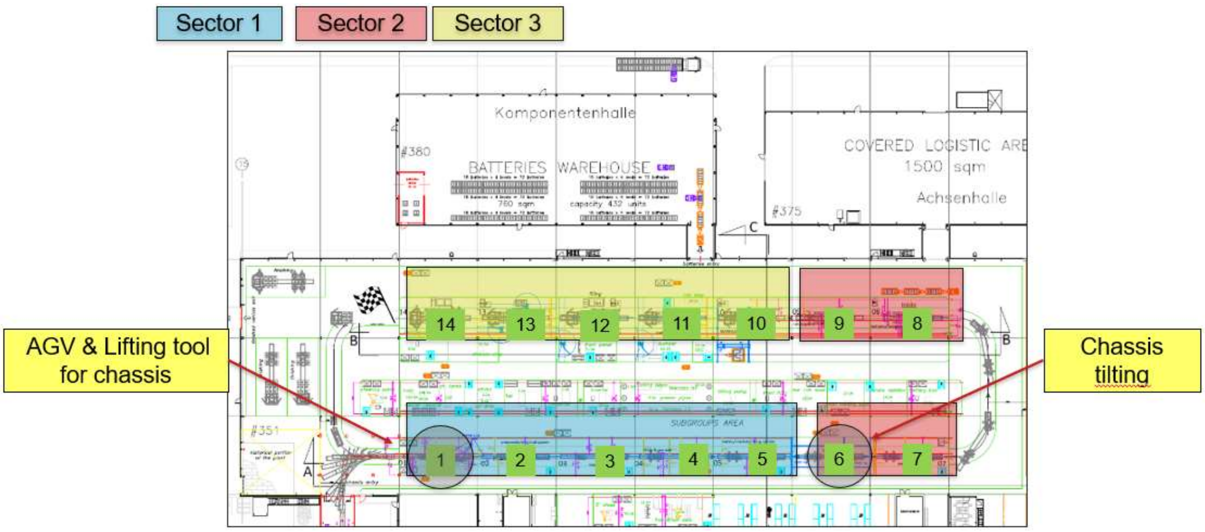


Figure 7.1 - Nikola Iveco Europe Manufacturing Plant Layout, ULM Germany

plant is composed by 14 workstations divided in three main sectors. Chassis arrives from an overhead conveyor and is placed on two AGVs. Basing on the version and so on the length of the frame, the AGVs adapt wheelbase automatically. Main operations performed in workstations are:

WS 1. First operations are assemblies of various supports for suspensions and air tanks. Air tanks subassembly is mounted in front central position as well as the FUP. Specific components to be mounted in this phase are the DCDC converter and HVAC conditioning compressor. All these parts weigh from 50 to 100 kg so they are lifted with assistance of crane. Each of them is interfaced with crane by a particular hook which is specially designed for each part. At this point the engine compartment is already full of components.

WS 2. In this station pneumatic system is joined to the frame. Rear air suspensions are assembled and connected with pneumatic pipes. Low voltage harness is lied down, and the circuit is started to be connected. These cables are quite heavy since they are very long, all together weigh around 10 kg. Finally, first HV components are inverters which are placed on the back of the chassis. Since they are 30-40 kg heavy, they must be lifted with a hook and carefully placed on rear end of the chassis.

WS 3. This phase is characterized by parts which are specific only to the electric version of the truck.

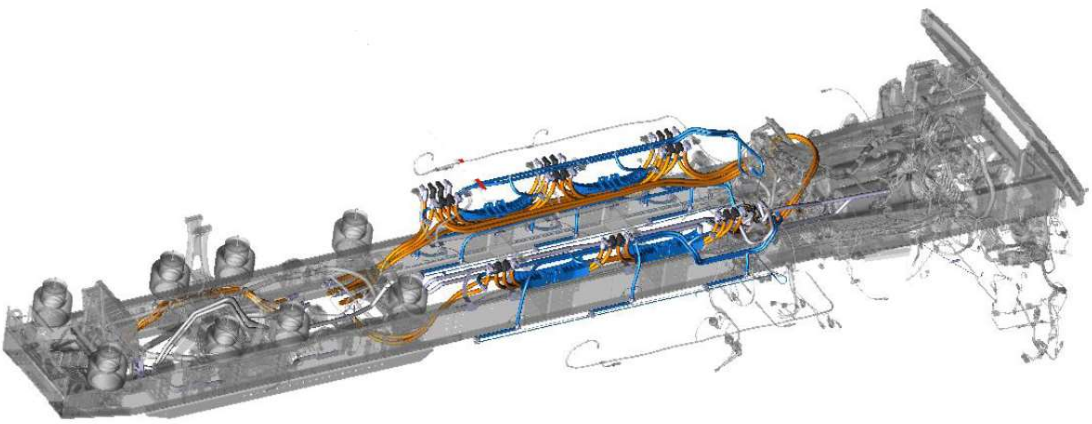


Figure 7.2 – BEV Workstation 3

First step is in fact to add HV harness on the entire frame. Harness is blocked to chassis with specific clips and is connected to already present components as inverters and converters.

This kind of power cables is very thick and heavy. For automotive application the conducting metal cross section goes from 10 to 120 mm^2. In the case of this truck, we consider largest cables with diameters around 12 mm. Cables arrive to the assembly station already cut to correct length and with

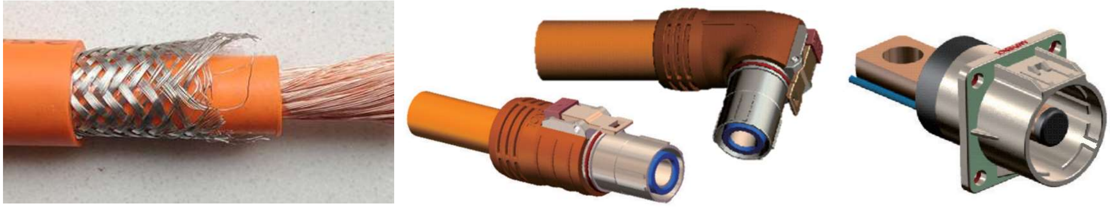


Figure 7.3 - HV Power Cable and Connector

connectors. They have to interface safely with battery and must have small trigger that ensures strong linking. Cable ends can be straight or angular depending on specific geometrical constraints. Since there is small gap between batteries in vehicle, in this case angular connectors are preferred. If otherwise HV components as converters must be linked, straight cables are chosen. Power cables must be shielded and must be of orange color in order to be clearly recognizable. Conductor is usually copper for its good characteristics, since the cross section is very big, a lot of material is required with significant costs. Insulation layer is made of silicon rubber and includes also metal shielding. This layer has many goals as to avoid any possible short circuit that would happen if conductor went in contact with chassis ground. Further goal is to give fire protection to cables so that short-circuit is delayed as much as possible in case of flames. General protection from exterior damage has to be guaranteed so that safety of who is present around cables is always ensured. At the end the cable has diameter of around 24 mm and is quite heavy and rigid. For this reason, since from vehicle designing operations is crucial not to have tight turns of the cable to allow the assembly process. Cables are lied down on the frame and fixed with specific metal supports. This condition is crucial to allow consequent operations. Wires are very bulky and rigid and could cause interface problems with successive assembly processes.

A crucial connection is the ground of each battery with the chassis. This joining is predisposed in this station where one end of the cables is bolted to the frame and the other end is left free for further linking.

Another specific system is the series of cooling pipes which are connected in the central part of the frame where batteries will be assembled. These pipes are very different between each other and have specific turns. They arrive to the assembly workstation already cut and shaped to the right dimension. This leads to a high number of different pipes that as is done for HV cables, must be fixed to the chassis with bands on supports. Same thing applies to the cooling circuit in the rear where e-axle and inverters will be positioned.

WS 4. Fourth workstation concerns the assembly of very bulky components which are mainly the suspensions and drivetrain.

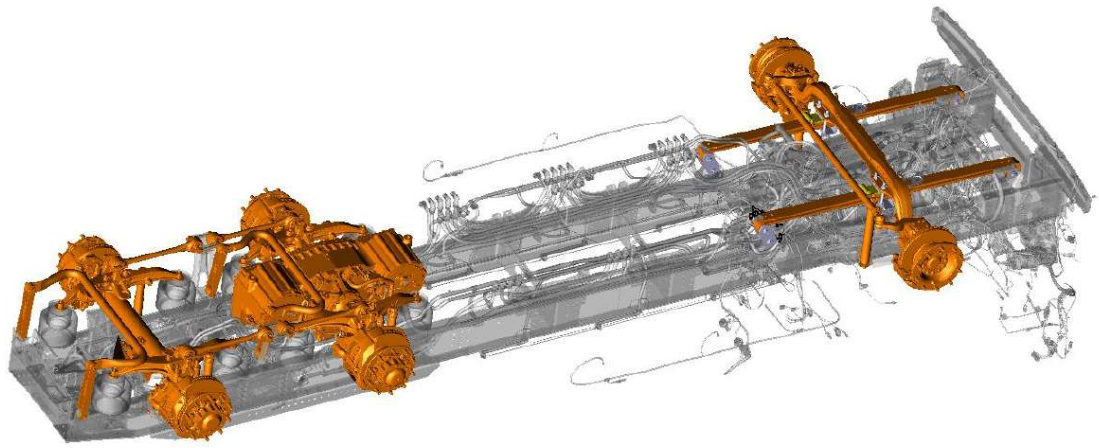


Figure 7.4 – BEV Workstation 4

Starting from the front, axle is mounted on leaf springs and locked with U-bolts. Shock absorbers are also added. Same happens for the very rear suspension.

E-axle is composed by two AC induction motors assembled together with transmission box. E-motor is composed by stator, rotor ad casing which are produced in an almost completely automated process. Assembly operation starts with stator cylinder which is just made of metal and has longitudinal slots cut in the inside part. These cavities are filled with plastic gaskets which can be seen in white in figure. These gaskets fit the slots and create housing for wires. Next operation is performed by winding many kilometers of copper

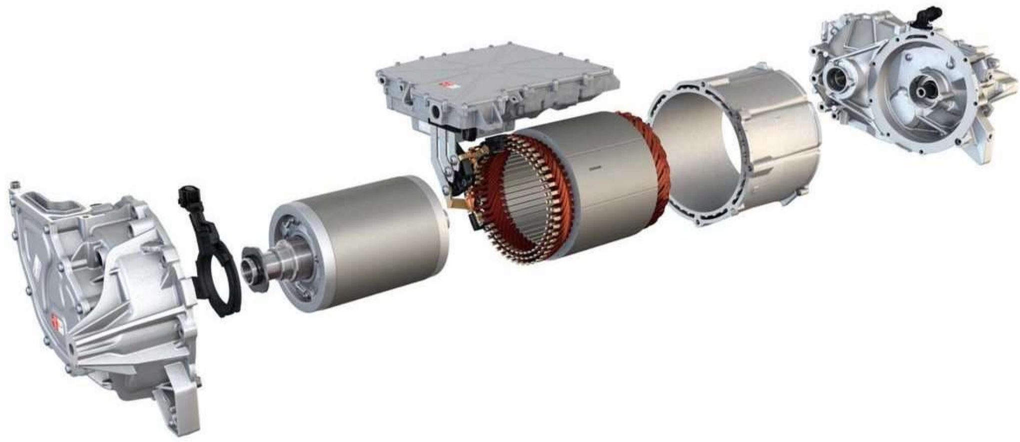


Figure 7.5 - Automotive Electric Motor Exploded View

cables on the stator by placing them through the slots. One end of the cylinder will have exiting and entering cable forming a U shape, the other end will have cable ends left free. At this point, these ends must be protected with plastic cover and with interface pins in order to create the three connection cables (positive, negative, ground) of the motor. With an automatic sewing machine, the wirings on two edges of the cylinder are enclosed with nylon stitching. Now the stator is ready and will be joined to other parts. Rotor manufacturing starts with winding of cobber cables on cylinder's exterior surface. They are placed in a way to create different coils in direction perpendicular to cylinder axis. Then, a shaft is pressed in interior surface of the cylinder and rotor is finished. The two components are assembled together and then placed in a housing. This casing is composed of two electric motors and a drivetrain made of gears. All the assembly is enclosed with sealant and a lid bolted on top.

E-axle arrives to side of vehicle production line and is very heavy, is married with the chassis with particular care. This subassembly weights around 1.5 tons and must be mated with air suspensions and rear axle. Is crucial that the two installed axles are parallel between each other. In addition, they must be centered with respect to the chassis so that at the end the vehicle is able to go straight. This condition is guaranteed by axle parallel check system which is composed by a camera, some gauges and hub adapters which analyze the vehicle rear and suggest how many shims to use to have parallel axles. Toe-in/out of the axle is also analyzed. At this point no connection is performed and e-axle is left free of HV cables and cooling pipes.

WS 5. In this step the other carry-over components are mounted as stabilizer bar or tilting cab cylinder. A specific assembly is the battery support brackets. These parts create the housing and protection of those accumulators which are installed on the sides of the frame. For this reason, a special tool is required in order to have correct dimensions of the housing. Only with supports placed in exact position will be possible to have correct interface of bolts which ensure the battery to the chassis.

WS 6. Sixth workstation is characterized by frame turning. As in all commercial vehicles the first operations are performed with upside down chassis and so at some point turning is required. This operation is performed with two particular cranes which are joined to the two ends of the chassis. Cranes lift the frame and with a belt, rotate it and place it again on the AGVs.

WS 7. When the frame has been turned around, it is clear that many different mountings become possible. Some completions are done on rear axle and air compressor is assembled at the front. Specific actions are the connection of both thermal and HV system to the e-axle. Same is done for the inverters.

WS 8. In this workstation batteries are assembled on the vehicle. These components arrive already tested and enclosed by the supplier. Batteries are made of series of cells which are assembled in modules and finally in the pack. Cell is the smallest unit of the battery system, and its manufacturing process starts with mixing. In this operation active material and conductive additive is mixed with binder to form a slurry. Two different mixtures are created for cathode and anode, and both are then pumped in a slot die where they are coated on both sides of a metal foil. Is necessary that all the solvent is evaporated and is done in drying operation. For environmental requirements is crucial to have emissions treated and solvent partial recovery. Calendering is then performed on material by passing between rolling mills. This process enhances the density, conductivity, porosity characteristics of the electrode. At this point electrode material is ready and must be stamped or slitted to the required dimension. Further drying is performed in a vacuum oven and moisture level is finally checked. After these processes, electrodes and separator have been produced and are ready to be assembled together. They are stacked layer by layer and then the connection system is welded to the cell. Finally, the cell is moved to desired casing which is filled with electrolyte and definitively enclosed. First testing is performed by activating the cells with low voltage and some charge/discharge cycles are performed. If some gas is expelled it must be correctly treated, then final sealing is performed.

At this workstation, each of the nine batteries, after being finally tested, is lifted, and mounted on its supports. Every pack weighs around 500 kg and must be initially joined by a special hook with four bolted ends and then to chain and crane. Pack is lifted and positioned in the correct location. Is crucial to well guide the descending movement of the battery in order to avoid any possible damage. Then the pack is joined to the chassis by 6 bolts, one at each of the vertexes apart from those two where battery interface is present.

Then the only connection which is performed for now is with the ground cable.

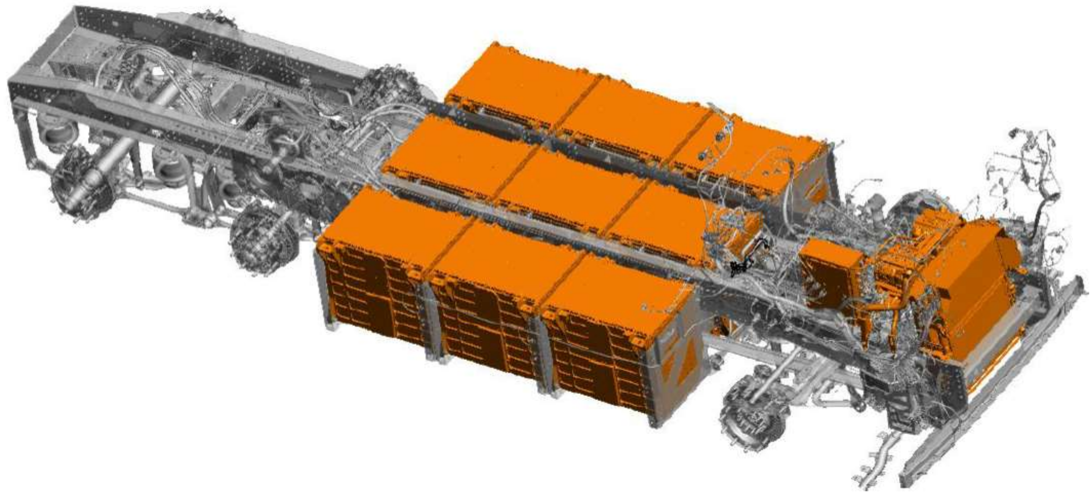


Figure 7.6 - BEV Workstation 8

At the front of the vehicle various components are added as the PDU (Power Distribution Unit) and radiator.

WS 9. At this point many smaller assemblies are performed. LV battery box is added as well as the steering pump system. Cab suspensions are mounted and rear exterior trim. First filling operation is performed with steering system liquid.

WS 10. Cab marriage is the main procedure performed at this step. Cabin arrives to side of the line and is lifted. Since it weights around 1 ton, with big care is placed on its support and is interfaced with systems. Steering column arrives already in the cabin and is connected to its system. Batteries cooling pipes which are at the top are connected and every single one is topped with the catwalk.

WS 11. Exterior trims are added at this point. Bumper is joined by ensuring correct position and gaps with other parts. Cab steps and other body components are installed at the side of the cabin. At the rear, spare wheel and 5th wheel are mounted while the windscreen fluid tank is filled.

WS 12. In this workstation the vehicle is very close to its final form. Front panel is added with the same care of the bumper. Air conditioning and pneumatic systems are filled while a particular device tests the wheel alignment and suggest corrections. In this station starts the programming of all ECUs and homologation plate is printed.

WS 13. Wheels are assembled only at this step. They are ensured with 10 bolts and tightened with a big electric screwdriver which guarantees correct torque. TPMS sensors are then scanned assigned at each wheel.

WS 14. Final station is the one at which the AGVs detach from the vehicle because it can stand on its wheels. Cooling fluid is loaded and so, at this point, every system is filled with correct liquid. Vehicle is lifted with two lifting platforms. This is done in order to be able to connect batteries to cooling pipes and to HV harnesses. This operation must be performed at the end of the line for safety reasons. Before this final workstation all the battery connectors must be protected with plastic cap. Another crucial condition is that the dummy MSD is mounted on the pack so that there are no risks related to electricity. Must be added that all HV connectors are made in such a way that voltage is only present well inside and all the exterior part acts as protection. From underneath the vehicle is possible to connect all the HV harness with particular safety measures. Then also the cooling circuit is completed with lower pipes.

Final step is the replacement of MSD connector with live MSD so that batteries are finally connected to the vehicle. Vehicle can leave the final workstation with the electric power in batteries.

TESTING. As all the normal vehicles, functional test is the first to be performed on the truck. This operation aims to check that every feature present on the vehicle is working properly.

If everything works, the vehicle is moved to next station which is composed of roller bench used for dynamic testing. Vehicle is accelerated following a test-driving cycle and its performances and energy consumption are assessed. Battery state of charge is in fact checked at beginning and end of the test.

If everything is acceptable the truck is moved to the following station to do wheel alignment check and sensors calibration. As the vehicle enters in this station hub adapters with cameras are mounted on wheels. These components with some targets placed in the room are able to measure and give live values of total toe, individual toe, thrust angle, position of steering wheel with respect to wheels, max turn. An operator can go below the truck and align wheels correctly acting on suspensions. When everything is within tolerance limits, a target rises in front of the vehicle and Adaptive Cruise Control is calibrated. Then Lane Departure Warning System follows the same calibration sequence and vehicle is moved to next tests. For all sensors and radars, calibration is very important, is done to ensure that are perfectly in line with driving direction. If a misalignment is present, some errors could affect the correct working of the assistance systems.

Brake test is performed on moving roller bench. Truck is placed on rollers and wheels start to turn. Then the operator brakes so that is possible to understand if braking system works properly and also if regenerative braking recovers energy. Headlamps are trimmed with a device so that their light rays fall into a specific shape.

Vehicle then goes into the water cabin to check the absence of any leakage. In this cabin, vehicle stays around 10 min and is sprinkled with water from top and sides.

Exterior trimmings are mounted as side battery protections and aero kit if other tests where passed. Next operation is vehicle weighting to understand if some components were not assembled.

Truck is finally moved to charging station where it is rebalanced and charging operation is controlled. This process is done by a charger which is able to send high power current to the vehicle. Vehicle is connected through power port and can be recharged with up to 350 kW.

7.2. Management of Batteries

As introduced in vehicle's specification chapter, high voltage system is mainly composed by batteries, harness, and motors. Biggest care must be assigned to batteries since they are considered as hazardous material and their malfunctioning may create serious hazards to workers in the manufacturing plant. In additions these items are very costly and are crucial for the customer most important parameter which is the vehicle range. Before entering into details of which are the best procedures to manage batteries, is important to start by introducing how is the battery pack structured and which are the main interfaces with people.

Battery pack consists of a series of modules assembled and protected by a metallic case. Energy storage is performed in modules which are 8 in this specific pack. All the other components are there to manage the modules and are mainly the BMS (battery management system) and battery disconnect unit. Everything is connected with both high voltage and low voltage wires, and then is cooled by a series of cooling pipes. BMS has the role of controlling battery status by monitoring main parameters which are:

- Voltage: both total and of individual cells.
- Temperature: measuring cooling inlet and outlet.
- SOC
- SOH: % of full charge available with respect to nominal capacity.
- Current.

BMS is also there to monitor charging situation both from charger and in regenerative braking.

From the outside the casing has holes for assembling operations and connectors for all the electrical linking.

HV connection is performed by 2 pairs of connectors and allow in this way to install two battery packs in parallel. Low voltage connection is composed by CAN bus architecture and is crucial to communicate with BMS. MSD (Main Service Disconnect) is a very important connector for safety. When battery is shipped a fake

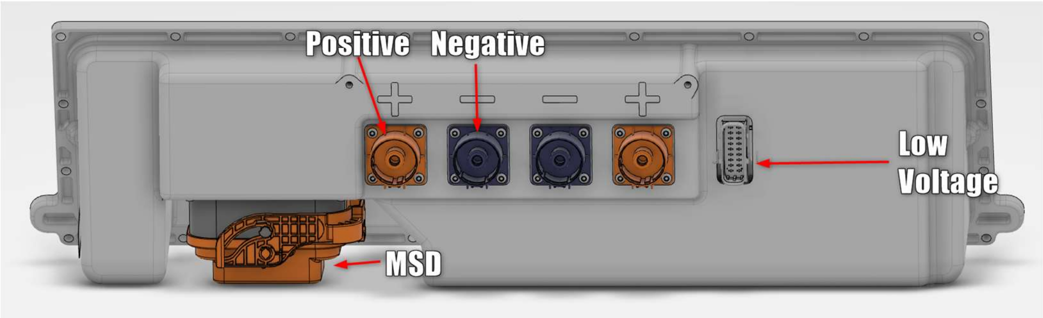


Figure 7.7 - Battery pack interface

MSD is placed at this port and it disconnects the battery. In this condition is enough safe to work around the battery pack. At the end of the production line this object will have to be replaced with a real one called "live MSD" in order to power the vehicle. Inside battery pack there is also the HVIL (High Voltage Interlock Loop) which is there to protect people who come in contact with high voltage in all battery lifecycle. In particular, this system acts as circuit braker and alerts the driver that failure has occurred.

Another critical component in the high voltage system is for sure the HV harness. High currents and voltages are transmitted through large cross-section cables and so many risks are present. Cables must interface with correct HV connectors and must have accurate shielding to avoid all the possible risks. All the connectors and cables are studied to avoid any possibility that people could get in touch with conducting metal. Connectors have the high voltage pole very protected from plastic covers. Cables have very thick shielding and connectors at their edge are built to interface with the one of the batteries, for this reason, safety of the assembling or disassembling operations is enhanced.

7.2.1. Battery shipping

Shipping batteries can be hazardous since the delivery conditions are not monitored during the travel and temperature can go outside of the acceptable limits. In fact, this kind of product is classified in "dangerous goods" for ADR, RID, UN, IATA regulations. Li-ion batteries are in class 9 that specifies miscellaneous dangerous goods. This classification means that accumulators can potentially generate hazard to human health and safety, infrastructure and/or their means of transport. Miscellaneous denotes that this product does not fall in other risk classes. Others are flammable, explosive, toxic, oxidizing, radioactive and corrosive. For UN regulations the Lithium-ion battery falls into the code UN3480 and so it must always be showed on the box in shipping operations.

In general, correct temperature range is from -20÷50 °C and in certain conditions is not so difficult that these limits could be overcome. Transportations implies also charging and discharging operations which could lead to shocks or impacts for the batteries. For this reason, is crucial that batteries are packed carefully to reduce

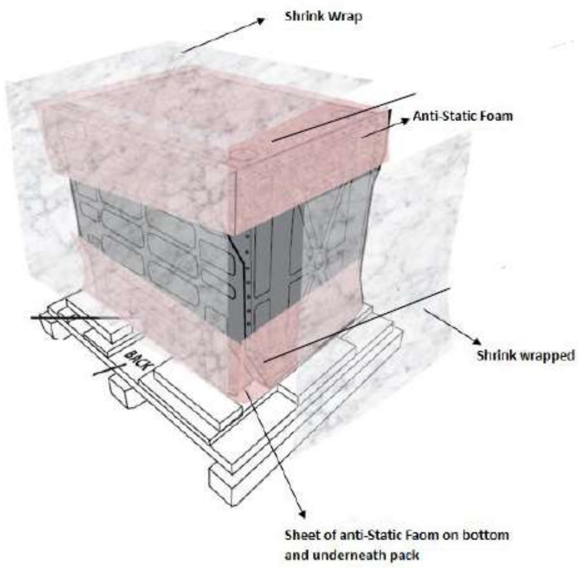


Figure 7.8 - Wrapping of battery pack

risks of damaging the cells. Packaging operation starts with application of antistatic foam on top and bottom. This foam ensures protection of the battery pack from static discharge and allows to have all electric charges dissipated safely.

In addition, the battery is shrink wrapped to have it completely closed and protected from the outside. Then the accumulator is positioned on a crate that will be the base of the shipping box. The crate is very similar to a wooden pallet but with the adding of some wooden blocks which prevent the pack from shifting sideways. Wooden frame walls are nailed to the base so that to have a semi-closed box. To strengthen the packaging, 2x4 and 4x4 (wood beams) are added and screwed. Finally, the top is screwed on the box, the crate is labelled and finally straps are mounted.

Label must contain:

- Full name and address of shipper and receiver
- ID Number
- Net Quantity (kg)
- Proper shipping name ("Lithium-Ion Batteries")
- Class 9 label and "Cargo Aircraft Only" label

When pack is shipped must be always accompanied by CoC (certificate of compliance) and all shipping documents (BOL, packing list, safety data sheet,

Figure 7.9 - Final Battery Packaging

shipper's declaration). Pack is shipped and stored always at 30% SOC for safety reasons.

7.2.2. Battery testing

All the batteries must follow a certification procedure in order to have the homologation. In European Union this procedure and requirements are defined in ECE R100 Rev2 Norm. First requirements which are imposed are on building characteristics of battery pack. If everything satisfies the prerequisites is possible to follow a specific testing procedure to get the homologation.

Test sequence is:

- Vibration Test: 3 hours at variable frequency between 7 and 50Hz.
- Acceleration Test: made to simulate deceleration of an impact up to longitudinal 28G and transversal 15G.
- Crushing Test: 100kN correspondent to 1O tons laterally.
- Thermal Stress Test: from + 60°C to – 40°C.
- Fire Resistance Test: battery is exposed to direct flame for 70 seconds reaching 700°C.
- Short-Circuit Test.
- Maximum Temperature Test: operation at 60°C.
- Internal Resistance Check: over-charge and over-discharge test.

If the pack passes all tests is suitable to be mounted on vehicle.

Since batteries are quite hazardous components, the manufacturer checks each produced pack following a specific procedure. Then the battery is checked at plant arrival before storing and assembling. This procedure is explained in battery test chapter of this paper. Those tests are mainly done on the pack to check battery performances while the previous one is mostly related to safety.

Considering this specific battery pack, manufacturer follows a sequence of checks. In fact, after the production of battery packs, a long series of tests are performed to ensure correctness of the assembly operation:

- Communication check tests:

This test is the first to be done on the pack, it is started by connecting the junction box (HV connectors, MSD, and LV connector) to BMS. After that all the signals presence must be verified. Parameters are mainly voltage and temperature for each cell, module, or pack. In addition, a response must also arrive from coolant temperature sensor and flood sensor. If this test is passed, is possible to move to the HVIL test. This test is performed to assess the correct working of the Interlock Loop, and the correct behavior of the BMS to the engagement or disengagement of the HVIL. Is done by disconnecting one HV connection at a time and see if the HVIL circuit is broken and BMS recognize HVIL fault. Then by reconnecting the pole it must be seen that BMS restores the original working condition. So, at the end of this test is sure that BMS, HVIL and junction box work properly and all connection can be done.

- Hi-Pot Test:

Hi-Pot testing is performed to assess if the electric insulation of the pack is adequate. It is performed by applying high voltage to the pack to check if was built in correct way and dispersion and elimination are still at the designed level. With a device made specific for this assessment, ground and a pole are connected each time and insulation of the two is measured. Is done by passing very high voltage of 2280 V and measure the behavior. The acceptance criterion is that each pack has resistance of at least 47 MΩ and a maximum leakage current of 60 μA.

- Megohmmeter Test:

Megohmmeter test is done to verify the isolation resistance of the module and pack before the final pack enclosure sealing. The test is started by disconnecting 24V circuit of the battery and by connecting one pin of the megohmmeter to chassis ground and one other to each HV connectors. This device can measure the isolation resistance that must be at least of 48 MΩ.

- Pack Enclosure Leak Test:

This test is the first of EOL, is done to verify the pack seal integrity. In particular, the pack must fulfill IP67 regulation. This means that the device is protected from any kind of dust and can stay in water for 30 minutes at a depth of maximum 1 meter. This test is done with a pressure gauge connected to the battery hoses. With this system you must insert air in the battery until reaching pressure of 2 psi. After that pressure is reached inside, you must wait at least 10 min. After this period, you must record temperature, pressure, and consider them as starting values. After 30 minutes you must check again pressure and to be passed it must have decreased of maximum 0.1 psi.

- Coolant System Leak Check:

This test is done to assess the absence of any leak in the coolant system and also the ability to withstand classical working pressures. With a pressure gauge assembly, air is supplied from the inlet of the cooling system. It is supplied until reaching values of 41 psi, at this point every valve is closed and battery is left to settle for 30 min. This instant pressure and temperature are taken as start values. After 68 min are reanalyzed and pressure will not have to fall of more than 0.1 psi.

- Functional Check:

The purpose of this test is to ensure proper functionality of the pack's pre-charge, contactors, and verifies the BMS is correctly reporting the required values. Procedure starts by sending HV signal of connectors closure and verify via CAN Bus if they are effectively closed. Then verify HVIL working and check isolation resistance of the HVDC bus. Finally perform a high-power discharge of 10 seconds and measure internal resistance of the battery. If all these data result in acceptable values, the test is passed.

When battery pack is received at the plant, it must be unpacked in correct way and inspected. If and only if the crate is intact and undamaged, is possible to start by unscrewing the top and step by step arriving to the only battery. Battery testing is performed also after this operation. The reason lies in the fact that travel could have damaged packs or could have reduced optimal SOC. At the accumulator arrival is important to test all batteries and store in warehouse only the good ones. This test is a sequence of checks which aim to have a non-dangerous battery that could be stored without any risk.

Pallet arrives by truck to the plant warehouse and visual inspection immediately starts. Aim is to verify that the packaging material is in functional shape when received. If there are signs of damage is important to continue inspecting through the packaging to ensure that the damage did not compromise the content of the pallet. If everything seems ok the package must be opened, and the battery must be unwrapped from protecting envelope. Visual inspection continues in search of signs of damage on the pack enclosure. If some damage is found in the pallet or even in the battery is important to stop and avoid any risk related to high voltage. For this reason, the pack must be moved to quarantine rooms and then the supplier contacted to understand how to manage it.

Next passage in testing is to lift the battery from the crave and to place it on a test bench. All the pack assessment is performed by a device which is able to measure electric performance of the battery. Device can be seen in *Figure 21* and is just a computer which integrates many electrical components. Interface with battery is made with a series of connectors which are connected with a specific sequence.

First connection to be made is the ground of the battery to the ground of the device, this cable is crucial to measure insulation of the battery poles. Then low voltage contactor is joined and so will be possible to connect to battery CAN Bus and communicate with BMS and various sensors. Finally, all the high voltage connectors are attached, and MSD Dummy is replaced with MSD Live. Battery is supplied with 24V which turns on the CAN.

Now starts the real battery testing procedure and the voltage of each cell, module and pack is read from the CAN Bus as well as their temperatures. First crucial

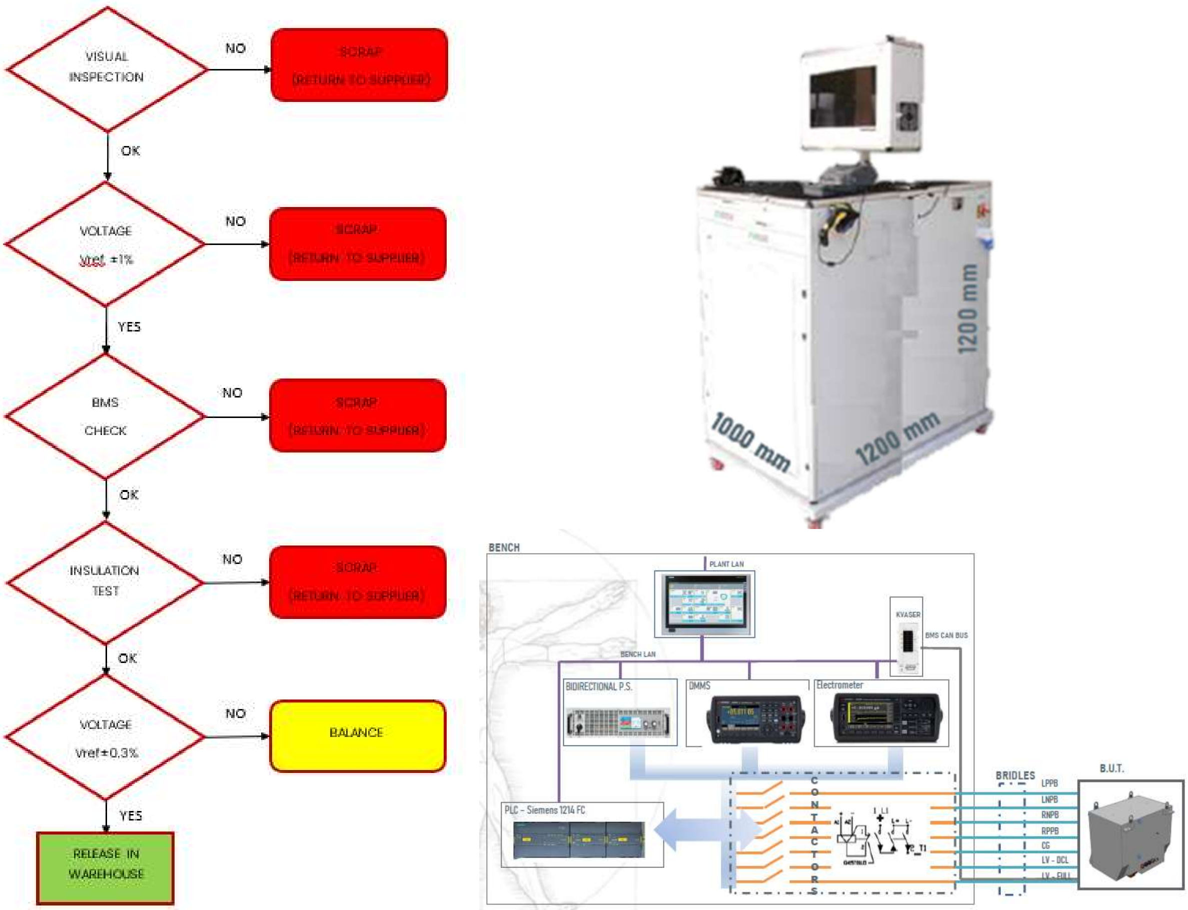


Figure 7.10 - Battery Test Procedure and Test Bench

acceptance criterion is that the pack voltage must be very close to the reference value at which it was shipped. This verification is also called SOC test since the voltage is directly related to battery state of charge. Usually, accumulator is shipped at around 30% of SOC to reduce fire risk. This first verification aims to understand if the pack was not impacted by travel. A threshold is placed around ±1% of the reference voltage in this specific case, but obviously depends on battery manufacturer specifications. If the charge is outside acceptability range the accumulator is scrapped and placed in quarantine rooms since it could be dangerous or damaged. If everything is ok, further tests can be performed on the bench. Next step is in fact to perform the BMS check. Objective is to understand if the BMS works properly and signals correct values for various parameters. Voltages and Temperatures must be correct and internal contactor closure must work. Isolation resistance measured by BMS must be greater than 480 MΩ and faults or alerts must be checked. Next step is the insulation test which is very important for safety. This test is performed by applying very high voltage to one HV pole at a time and measure the resistance and current with respect to ground. Resistance must obviously be as big as possible and very small current. Finally, last SOC test is performed and in order to see if the battery is charged to the right level and if not, it must be recharged in balancing operation. Balancing is done directly by the same device and is last testing operation.

Battery is then disconnected and placed again on its pallet and is stored in warehouse. When it has to be assembled, further tests are executed. Here many options are possible: first way is to perform same test procedure as previous. This solution is usually unnecessary since warehouse, if kept at right temperature, should never impact battery status. Second more simple option is to have a shorter testing procedure. By connecting just the Low Voltage interface with the battery, is possible to understand SOC and isolation. SOC test is done by comparing module and pack voltages with reference values and also with battery's previous values. At first test all the measured parameters are stored and assigned to specific battery ID code. In final assessment these values can be retrieved and compared, having a complete and reliable check of each single accumulator. Isolation test is performed just by reading BMS output and compare it with thresholds. This light version of test requires just CAN Bus interface and a computer. For this reason, testing can be performed in warehouse before sending to assembly line or even directly in workstation before the final installation.

7.2.3. Battery storage

Proper storage of Li-ion batteries is critical to maintain optimal battery performance and reducing the risk of fire. Fire risk is extensively explained in safety considerations paragraph.

Lithium-ion batteries are subject to aging phenomena which shorten their useful life and so reduce their performances. Aging is a loss of accumulable energy and

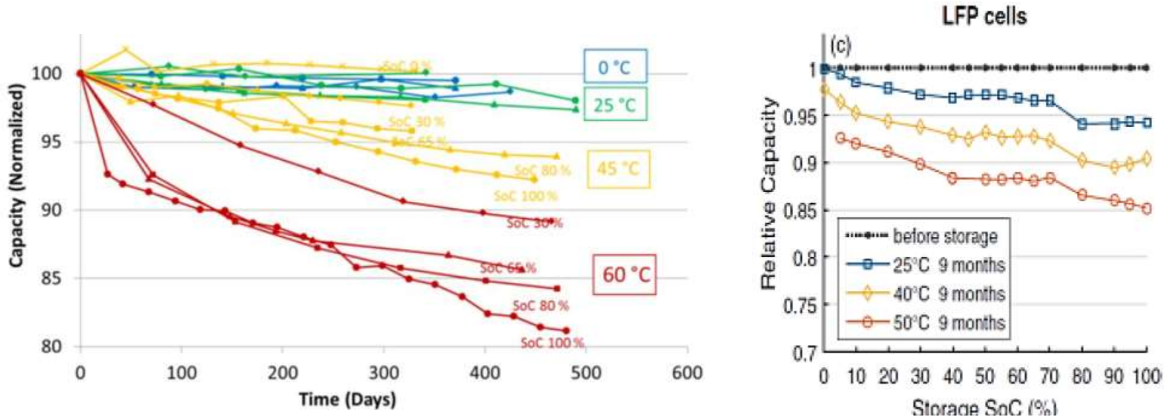


Figure 7.11 - Battery capacity loss in time

deliverable power associated respectively with the loss of capacity and the increase in internal resistance. Calendar aging is the degradation of the battery at rest over the time it is stored under Open Circuit Potential (OCP). Cyclical aging is linked to the actual use in the charge and discharge cycles. For what concerns storage the obvious risk is to have calendar aging and is dependent on storage time and temperature.

Temperature directly impacts the capacity of the battery as well as SOC. This is one of the reasons why the battery is shipped and stored at only 30% of charge. The other one is related to fire intensity, which is significantly reduced at this level of charge.

Each battery manufacturer gives indications on how to store the batteries to maintain them safe and to avoid performance losses. In this specific case battery packs should be stored in a cool, dry, and well-ventilated environment with a relative humidity of 40% or less. Battery packs should be stored at 30% SOC between

Duration	Acceptable Storage Temperature Range
1 Year	-20°C to +23°C
3 Months	-20°C to 45°C
1 Month	-20°C to 60°C

Table 7.1 – Acceptable Battery Storage Temperature Range

-20°C and +23°C for long term storage and always with coolant circuit fully drained. It is acceptable to store packs at more extreme temperatures for shorter durations. In addition to what is specified by manufacturer, each country has its own regulations for what concerns storage of hazardous material. In absence of specific legislation is important to have agreement of provincial fire brigade.

European legislation imposes that warehouse must be closed with REI 120 (UNI EN 13501) doors and walls which provide fire protection. A water sprinkler system is mandatory with a minimum capacity of 24 l/min for each square meter. Batteries must be stored on metallic racks and each level must have its sprinkler system. On the floor is mandatory to have a water collection system that in case of fire creates a big tub and collects all the water necessary to extinguish fire. Sprinkler system is activated by fire sensors which must be placed all over the warehouse. Best condition would be to store batteries far from each other to reduce heat propagation. Warehouse must avoid exposition of accumulators to direct sunlight or external heat sources. Batteries cannot be stored in mixed warehouse with other products. The extra product could impact fire risk and could act as accelerators in that case. Specific floor is required to store batteries. Requirements are related to fire resistance as well as specific electrostatic performance. The warehouse must be clearly marked on the outside as a storage place for lithium-ion batteries, with the indication of metal lithium for firefighters.

For what concerns the quarantine room, similar legislation is present. Separation is crucial with REI 120 certified walls and must have all the sprinkler system. Direct access is mandatory to the external and to the warehouse. A minimum distance of 5 meters must be always ensured between batteries and thermal imager must be present to continue to monitor packs' temperature. Finally, quarantine rooms must have water collection system, fumes detector and extraction system.

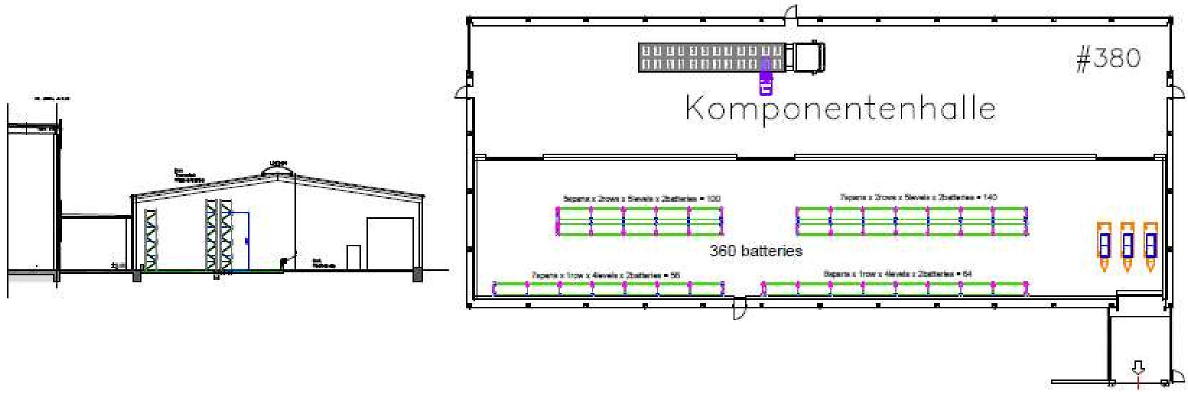


Figure 7.12 - Battery warehouse layout

In the above figure is possible to see a practical implementation of all the prescribed measures at ULM manufacturing plant. Warehouse is divided in two big areas. Top part of the layout represents the area where trucks can stop and be unloaded. On the lower side, zone with racks can be seen. All this area is enclosed and dug to be able to collect water from sprinklers. Batteries are stacked up to 4 levels and each one has its own dedicated sprinkler.

7.3. Safety considerations

Safety is one of the most important aspect which is impacted by electric vehicle manufacturing process. As we have already seen, many variations on the production line are due to safety problems. The two main hazards related to HV vehicles are related to High Voltage and Lithium-ion batteries.

High voltage can cause electric shock or even electric arc. This last phenomenon occurs when two points at big voltage difference are close, and an electrical discharge happens through a normally non-conductive medium as air. Electric shock happens if a person touches live parts. Consequences are cardiac arrhythmia, cardiac arrest (up to 24 hours after the electrical accident), burns, muscle cramps, renal failure. Severity of these depends on current and exposure time. Concerning DC current, up to 2 mA cannot even be sensed. Reactions start at around 200 mA and reversible damages are until 500 mA for short times. Above this limit irreversible damages are made on internal organs and death can occur. If AC current is considered, similar limits are present, but considerations must be done on frequency. Worst one is 60 Hz and risk decreases for higher frequencies.

Lithium-ion batteries can be source of many hazards as fire and can also spread very dangerous substances. First considerations are done on fire risk, main cause of battery fire is for sure high temperature. Major weakness of lithium-ion battery is its organic electrolyte. This is a liquid substance that is volatile and flammable at high temperatures. Batteries suffer thermal runaway events. This means that after the exothermic chemical reaction starts, it continues to grow with temperature increase. In that thermal accident, battery releases electrolyte and some other flammable gases as hydrogen, methane, and carbon monoxide. Cause of this phenomenon can be many:

- Electrical abuse: charging or discharging the cells with very high voltages lead to cell overheating.

- Thermal abuse: high external temperature can start to evaporate electrolyte and spark the chemical process.
- Mechanical abuse: crash may induce electrodes shorting and local heat.
- Internal short circuit: If separator fails, anode and cathode come in contact and short circuit occurs.

Problem is that thermal runaway of a single cell that usually leads to fire of the entire pack due to the easy spreading of the reaction. In a warehouse this phenomenon could also lead to firing of all the present packs. Fire suppression can be made with large amounts of water to cool the battery and avoid heat propagation. Best solution would in fact be to submerge the pack in water, in this way also adjacent cells would not be included in the reaction. There are also other kinds of extinguishers specific for Li-ion batteries, examples are halogenated or powder extinguishers but do not have significant advantages.

7.3.1. Working with High Voltage

High voltage risk mitigation starts with classification and training of the personnel in order to have correct electrical expertise to perform each operation. Starting with Italian Legislation, following CEI 11-27 Norm possible to divide working people into 4 categories:

1. PEC-Common people: No expert and even not informed about any possible risk. In this category fall every worker of the assembly line as well as the external people. Usually very short training is given to this people of about 1h involving general risks and protections required for working far from electricity.
2. PIN-Informed people: Do not work in areas with high voltage but are well informed on risks and precautions. Examples of people are logistics and quality operators which must move the batteries. For these people are usually necessary around 4 hours of training to have sufficient knowledge.

3. PAV-Warned people: Warned by expert people, able to get close to high voltage knowing which are the specific risks and avoid them. In this category fall testing operators, those who have to work close to electricity after the vehicle is fully connected. In this case a very much longer training is required of around 8h.
4. PES-Expert people: Enough knowledge to be able to analyze risks and avoid hazards in working close to high voltage. In this category we find electricians and operators which must act on high voltage system after it is connected. These people must have prior complete knowledge and are trained with 16 hours of course.

The consequence of this classification lies in the division of the high voltage proximity areas in four areas.

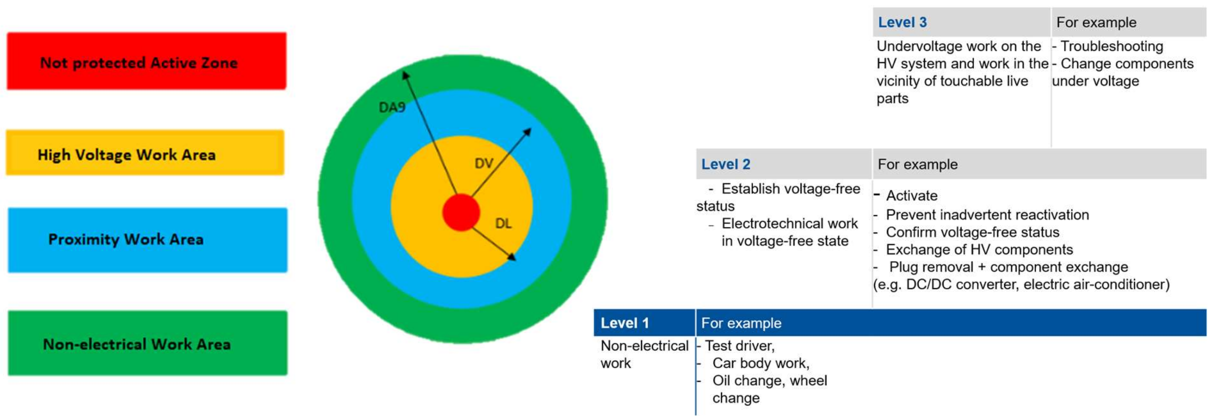


Figure 7.13 - Areas nearby HV System and DGUV 200-006 classification

PEC can only stand in green area; PIN can go closer to electricity but only until blue area. PAV and PES can work in the yellow area and so they can get in touch with electrical system. This regulation affects a lot the operators' choice in manufacturing process. There is need to train everyone and also to have specific very trained people to be able to perform operations on HV system.

Another legislation is the one related to Germany called DGUV 200-006 which is specific for HV systems on vehicle manufacturing process. First step is to well define what is High Voltage, following this norm it is about $60V<x\leq1500V$ DC voltage or $30V<x\leq1000V$ AC voltage. For this regulation are present three levels:

Level 1. Non-electrical work: Training is intended to raise the employee's awareness of the HV systems in order to enable them to work safely on the vehicle. The objective is for employees to be able to operate the HV components safely, to understand their structure and principles of operation, and to be familiar with the markings of the components. Also, must be clear that works on HV systems are not allowed and could lead to high risks.

Level 2. Electrical work in non-live state: This training is required to make any electrical work on vehicle. Training depends on background of people and is adapted to people's expertise.

Level 3. Electrical work in live state: Live work on HV system requires a further instruction. This training goes really in depth of the matter including also practical exercises.

For commissioning of HV batteries is always required a level 2 operator. Same level is required for reworking activities which are not directly made on HV live parts. If an electrical fault has occurred will be necessary to have a level 3 technician in order to have it repaired.

High voltage risk is started to be mitigated by previous regulations and so the knowledge of systems structure is the base of hazard prevention. This approach is clearly not enough and so must be integrated with other protections.

Figure 7.14 - High Voltage PPE

Every operation performed on live HV system must be computed mandatory with Personal Protective Equipment. Specific PPE is required and is composed of:

- Insulating gloves: there are present many versions made of various materials. Each one of them can withstand a voltage level. Class 4 gloves for example are the most protective ones and can insulate up to 36 kV AC and 54 kV DC. Material is usually rubber and can be wear with leather over-gloves to extend their life. Gloves must withstand periodical testing procedure in order to be always sure of their integrity.
- Insulating boots: protection with the ground is crucial in order to avoid electric discharge through the body. These specific boots are made of rubber and have steel reinforced toe cap. They can sustain 20 kV for at least 8 hours, and up to 35 kV.
- Arc flash helmet and visor: this device is used to protect eyes and face from arc flash events. They are important in cases of electric explosion events since sparks and light flashes are emitted.
- Protective workwear: these protective clothes are insulated against high voltage. In addition, they must offer fire protection.
- Electrical safety hook: this device is mandatory in areas where works are performed on HV systems. This hook has the goal of allowing safe rescue of electric injured people. If rescuer touches an operator which is still attached to high voltage source, he as well can get injured. This hook allows to retrieve the injured person while maintaining a safety distance and avoiding any possible electric hazard. This stick must have very good insulation of around 45 kV.

7.3.2. Electric Vehicle Management

A crucial part of the manufacturing process of a vehicle is the rework. There are many causes at the base of possible reworking. An example could be a damage on an assembled component, the absence in line of a non-blocking part, or the non-correct operation of a system assessed and end of line. No matter what the problem is, there is always requirement for few stations with dedicated technicians able to solve issues. In the case of BEVs a series of complications arise since in many cases the operator must work close or directly on an HV system. Same considerations can be done for aftersales assistance. Each repair workshop will have to adopt safety measures to accept electric vehicles. Problems in management of BEVs are not over; in accident situations there are very specific predispositions that must be followed to protect rescue people. Since this paper concentrates on manufacturing process, some considerations will be done focusing on rework areas.

Whenever some works have to be performed on an electrical vehicle which is turned in live condition, some safety measures have to be considered. Is mandatory that the operator has correct knowledge defined by training levels and always must wear PPE. A simple approach is the adoption of five rules:

1. Disconnect: most important step is this one, is crucial that this operation is performed in the right way. During disengagement there are many risks mainly related to possible electric shock and arc. For this reason, only qualified people can perform disconnection and reconnection. Depending on vehicle structure, disconnection can be indirect through diagnostic device or directly on HV system.
2. Take the necessary measures to prevent reinsertion: for direct disconnections is possible to use a single key lock directly on the HV system. In this way is sure that no one will reconnect it apart from the working technician. Signs must be attached on vehicle and the area must be

delimited with specific barriers. Electric charge port must be covered with adhesive sticker in order to avoid recharge.

3. Check the absence of voltage: voltage is measured all over the vehicle with a voltmeter before any work is done. With the same tool is important to check the electronic circuit board and also the 12V system.
4. Ground and short-circuit: always connect the ground cable so that the vehicle is short-circuited.
5. Protect yourself from nearby live elements: although all these passages are ensuring quite safe working environment, the operator must always wear PPE in all its components.

Another important prescription is related to the fact that operators performing works on vehicle should never be left alone. In case of an incident with high voltage is very important the quick intervention of another person who can disconnect the electric system and separate the injured person from it.

8. FCEV vehicle manufacturing process

8.1. Manufacturing process

Manufacturing process for fuel cell version of the truck is quite different from the electric version. Since the two variants of the same vehicle have to be produced on same production line simultaneously, similar processes have to be organized in order to have assembly of common components at the equivalent stations. Even if could sound easy, this operation is quite difficult to manage. Since heavy-duty truck are always produced in a wide variety of versions, production lines are very versatile and can be adapted. In this case only the key differences with BEV manufacturing process will be explained. Main changes at each workstation are:

WS 1: Air tanks are not mounted in front central position of the chassis but supports for fuel cell are assembled. This operation is similar to what is done for traditional internal combustion engines. Then support brackets for the hydrogen tanks are added on top of the frame. This structure is what will join the vertical back-pack structure to the chassis and so will have to sustain significant weight.

WS 5: In fifth step no battery brackets are mounted since there are not side packs to be installed. At their place the support brackets for side tanks are installed. These components are L-shaped and have holes to interface with the tank structure by bolting. Battery supports are mounted in the center of the frame. In addition, the exhaust system is added since the chassis is still in upside down condition. Exhaust system is just a series of tubes with no particular material required. This system must just expel all the water coming from fuel cell and so not leak any hydrogen if some residue is present.

WS 7: Fuel cell is installed at this step. This operation is similar to engine marriage of the traditional diesel semi-truck.

Fuel cell stack is composed by electrodes membrane, gas diffusion layer and bipolar plate. CCM (Catalyst Coated Membrane) is present in two versions as cathode or anode. It is made of a polymer which is coated with platinum for both cases. Differences lie in the materials concentrations.

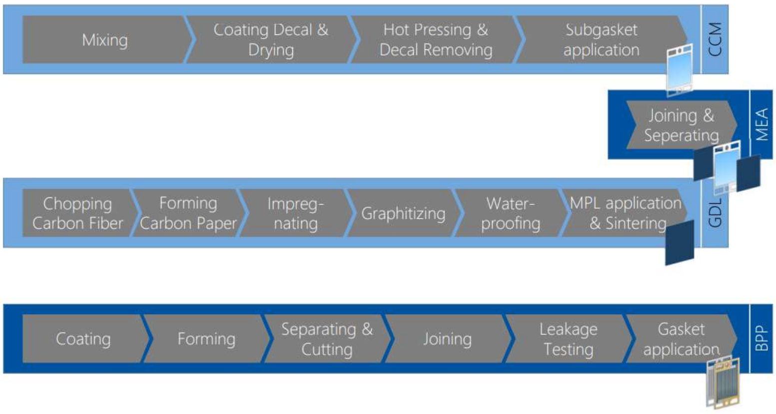


Figure 8.1 - Fuel Cell Components Manufacturing Process

CCM manufacturing process starts with mixing of catalyst powder, solvent, and binder. Slurry is pumped in a slot die where it is expelled on a decal which is unwound on rollers. Thickness of around 15 μm is coated on the decal and then is transferred to convection oven to dry. Then by pressing with hot rollers the coating is transferred from decal to the polymer membrane. Cathode and anode decal are fed directly on top and bottom of membrane and are simultaneously attached. At this point the CCM is ready, composed by a cathode, an anode and polymer in between.

GDL (Gas Diffusion Layer) is manufactured starting by chopping carbon fiber with a cutting wheel. Fiber is cut in transverse direction to break the filaments. Chopped fibers are pressed together with a binder to form carbon paper which is passed in calendering with hot rolls to get dried. Next operation is the impregnating of the paper with a thermosetting resin that gives particular physical and conductive characteristics. Then paper is pressed to remove solvents and finally dried in an oven. Graphitization or high temperature carbonization of the resin and leads to high conductivity and higher modulus o elasticity. Is done by heating paper at around 2000°C for around 5 min. Final product is around 300 μm thick. Then the material has to be waterproofed by passing in an aqueous solvent and cured in an oven. Finally, microporous layer is applied and sintered, and the layer is ready for assembly. This is done by joining two GDL layers on top and bottom of CCM and pressing together with rollers. At the end the foil is cut in smaller parts.

BPP (Bi-Polar Plate) is produced starting by coating raw material with an ionized substance. Then by hydroforming the final shape is given to material and with a laser is cut to correct shape. A welding laser beam is used then to join two half plates together to get final plate. This component is tested in search of leakage by pressing gas as helium inside. Finally, a gasket is applied.

Fuel cell stack is finally assembled by placing two BPP at the edges. In between are assembled two GPD and in the center there is the CCM. Then the stack is pressed and tested for leakage and proper functioning is assessed.

Fuel cell arrives already completed and tested from supplier with all connections closed. This is crucial in order to avoid any contaminant infiltration

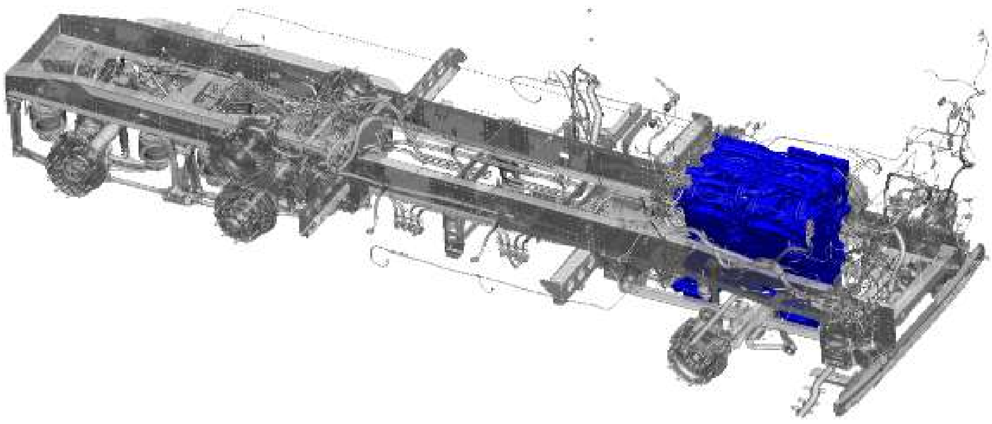


Figure 8.2 – FCEV Workstation 7

that is very detrimental for this system. Hydrogen converter weighs around 750 kg and with aid of crane must be carefully installed in its position. Difficulties are related to tight spaces and tendency of cables to get pinched. When assembled, it must be bolted to the supports and connected to HV and cooling systems. Joining must also be done with air intake, hydrogen pipes and water exhaust system.

WS 8: Eighth workstation is characterized by assembly of batteries as is done for BEV version. For this truck only two batteries are installed in center of the frame. In the remaining time, the three-tank structure is lifted and mounted on its supports. Automotive hydrogen tanks are made with a first plastic layer reinforced with carbon fiber winding. Manufacturing process starts with plastic injection molding for two halves of the tank. These two equal parts are welded together to form the entire cylinder. Then it is attached to a lathe machine where plastic container is wounded with fiber. In this case due to high working pressure, material used is carbon fiber. After it is completely wounded, composite is hardened with hot air and testing procedure is performed. At the end the tank is enriched with interface system and can be shipped.

Hydrogen containers arrive to the plant singularly from supplier and must be assembled together. The subassembly of three containers is called backpack and is very heavy, around 1300 kg. In subassembly workstation the tanks arrive

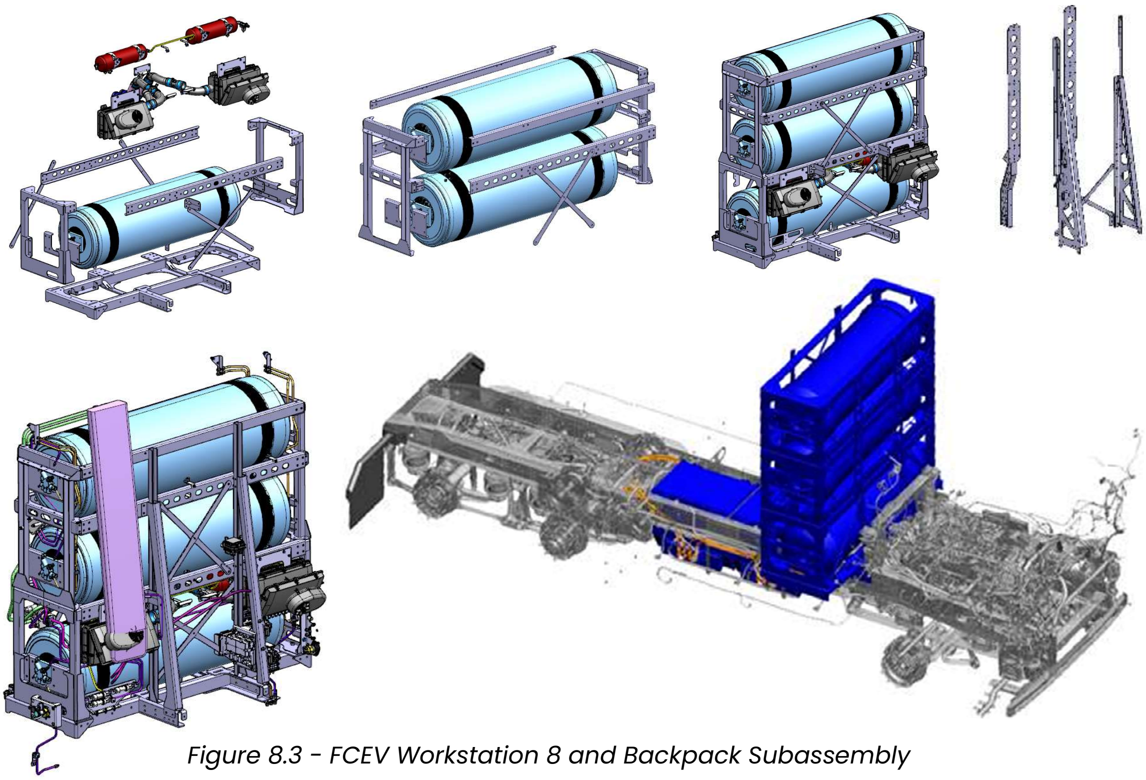


Figure 8.3 - FCEV Workstation 8 and Backpack Subassembly

already tested and certified. After a visual inspection the first one is placed on metal base and then enclosed with other beams. Then interface of the system is added on top of the cage. In parallel, the other two tanks are assembled and reinforced with cage. These two big components are joined and finally enriched with vertical supports which have the role of keeping the backpack in position with respect to the frame. At the end hydrogen pipes and valves are connected to all tanks and to the thermal system. A leak testing procedure is performed prior installation on vehicle in order to increase safety and reduce necessary reworks. Procedure is defined in tank management chapter.

For assembly operation, problem is caused by height of backpack. This structure is about 3.5 m tall and must be lifted well over the frame on AGV. Chassis supports are at a height of around 1 meter, for this reason is necessary that the lifting crane is able to lift up to at least 5 meters. This requirement impacts the production process since it requires very high building ceiling and crane support structure. In addition, being a very heavy component, this operation requires similar care to what happens for cabin. The backpack must be controlled with ropes in order to drop it in exact position to be mated with the support platform on chassis.

WS 9: in this workstation two side tanks are mounted. They are joined to supports and placed to the chassis sides. They are preliminary tested as the backpack parts. Assembly operation is quite complicated since the backpack interferes with on top of the tank. These components have in fact to be lifted and positioned in right spot arriving from the sides. Backpack does not in fact allow their drop from the top, so they must be pushed laterally. After having been bolted to the frame supports, the tanks are joined to pipes and valves in order to close the entire system. In this station also LV battery box is mounted close to tanks. In BEV it was positioned where now the fuel cell is placed.

WS 10: Cabin marriage is performed in tenth workstation. This operation is very similar with respect to BEV vehicle. Only differences are related to the fact that backpack constrains movement of the cabin around the workstation. Additional care must in fact be considered since impacts with tanks and fuel cell could cause important damages. Must be stated that gap between backpack and cabin back panel is quite small around 5 cm. For this reason, additional complication is added to an already intricate operation. Difficulties are not over, cabin arrives with special sealant and must not be scratched for safety reasons, leading to huge care required.

Another crucial difference of the FCEV vehicle is in fact related to cabin insulation requirements. As already introduced, cabin arrives from MADRID plant already finished and trimmed. Diesel, CNG and BEV versions' cabins arrive full of holes predisposed for successive assembly operations and for optionals. When it comes to Hydrogen, real safety risk is present and so the cabin must be adapted. As we know hydrogen tends to go up, cabin is exactly over the fuel cell and so a leak could get significant hydrogen concentrations in the passenger compartment. Is crucial that the cab is totally insulated. Manufacturing process cannot be however completely distorted since normal cabins still have to be produced and, in addition, this would lead to abnormous costs. So, at the end, an adaptation of the process is done starting with mounting of particular bolts with incorporated gasket. These joints have insulation characteristics and obviously an increased cost. All the holes present in the cabin must be closed with rubber or plastic plugs and then sealed. If holes are bigger than 20 mm they must be closed with a plug, on the contrary sealant should be enough. Consequently, all the floor of the cab must be sealed with a specific insultation foam in order to cover everything. In particular cracks and bolts could be source of leaks and with this sealant it should be avoided. Cabin should also be enriched with H2 sensors under roof and also under floor. Roof has to be modified with venting system able to expel any hydrogen if detected. Steering shaft is the main component which must pass through cabin floor metal sheet. This spot is very likely to favor hydrogen leakage in cabin and so it must be modified. Shaft must have new rubber grommet in order to allow its rotation avoiding any possible leakage. Finally, the cabin must undergo a validation process where it is placed in a cabin with high pressure H2. Any gas infiltration is spotted ensuring that the passenger compartment is really insulated.

TESTING: immediately after the vehicle has been fully assembled, it is tested for presence of leaks in hydrogen storage system. Vehicle is driven with electric power to a specific station to perform a sniffing test. Tanks and fuel cell valves are kept close and high-pressure gas is pumped into the hydrogen system at a pressure higher than standard. The system works normally at 700 bar maximum and for safety is tested at 910 bar. Used gas could be ideally hydrogen but would require high costs and specific safety measures which can be avoided with other gases. Helium is a good candidate for this application due to its dimensions, only problem comes from the fact that pure helium is quite costly to get due to the very complicated purification process. For this reason, best choice is a mixture of helium and nitrogen with 90% concentration of the first. Gas is stored in tanks and feeds a series of compressor that are required to get to high pressure. Then is sent into the vehicle and is kept in the system for required time of inspection. With an instrument called sniffer, is possible to get close to pipes and joints of the system and find any leak. Sniffer tool is very similar to the one used for natural gas vehicle and can be operated manually. It is a magnetic deflection mass spectrometer and must deal with a normal concentration of helium in atmosphere of around 5 ppm. Since in this case gas pressure is considerably high, a robotized movement of the sniffer would be preferred. This kind of robot would have a predetermined path to follow in order to inspect all the potential leaking spots. Choosing this solution would highly reduce risks related to system failures which could throw pieces away and injure workers.

If a leak is found, depending on its position, will be necessary to rework the vehicle or even to substitute components. Since safety is very important when considering hydrogen vehicles, it is always preferred to substitute with new parts.

Real implemented working cycle is structured in this way:

1. Vehicle is connected to pipes; safety barriers are activated.
2. Gross leak check: system filled with nitrogen at 50 bar, let stabilize and wait some time to measure any pressure drop.
3. Leak check: vehicle filled with 90% He and 10% N2 at 910 bar and kept for some time to check right resistance of pipes and connections.
4. Sniffer test: pressure is reduced to 700 bar for safety reasons, safety barrier open and operator manually place the sensor probe close to predefined connections. Test positions must cover all possible leaking spots and must

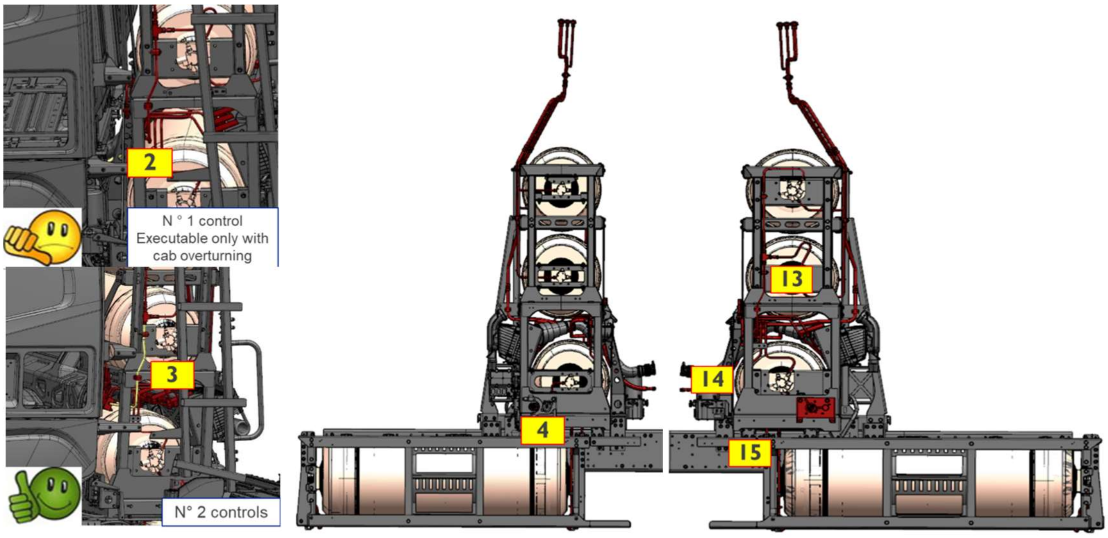


Figure 8.4 - Hydrogen leak check positions

be accessible. It is crucial that operator moves the probe all around connections since it is able to sense a leak only if placed very close and kept for enough time.

5. Gas recovery: a system of tanks and a vacuum pumps are able to recover about 75-90% of test gas. Lost gas must be refilled with a substitutable tank. This system is also in charge of creating with a compressor the test gas at 910 bar.
6. Truck is disconnected and leak test is passed.

It must be underlined that all the pipes arrive tested from suppliers and do not require further checks. This test is performed to assess correctness of pipe assembly and tightening of connections. Threshold for acceptance is to have a maximum leakage of 0.61 gr/y of hydrogen at 910 bars. This value has to be translated into an equivalent level of helium which is 1,0E-4 mbar/s at 910 bars.

Is very important to underline that test reliability is highly dependent on operator execution, so big focus must be posed to training.

At this point the vehicle high pressure system is safe and vehicle can have its batteries recharged for functional tests. This procedure is equal to BEV version and aims to find any failures in the powertrain, braking system and functionalities. If everything works properly the vehicle can be finished with aero-kit and side skirts.

Vehicle is finished but still has nitrogen at 5 bar in tanks and fuel cell which has never received gas. Truck is moved to a specific workstation to perform purging procedures. Tanks valves are opened whilst 350 bar hydrogen is pushed in the system to circulate. This process aims to remove any helium and nitrogen residues from the system, preceding the opening of fuel cell. This component is very delicate and must be passed only by hydrogen in order to maintain its performances. With purging is possible to recirculate a great amount of gas to eliminate alle nitrogen previously stored in tanks. All this gas could be recovered and filtered, or it can be dispersed in the atmosphere. Process ends when nitrogen concentration gets below 1.74% and so is safe to connect the fuel cell.

Next purging involves in fact also the fuel cell and is cleaned until same concentration is measured. At same station extraction valves are now closed and truck can be filled with hydrogen at 700 bar. The amount of fuel injected must be sufficient to perform further tests. Truck is in fact driven for some laps of the testing track in order to assess correct functionality of the entire powertrain, starting from fuel cell. Another solution could be to pass the vehicle another time in the functional area, but since it is indoor, it would require many safety measures that can be avoided in outdoor testing. Finally, the vehicle is completed and safe, and can be delivered to final customer.

8.2. Management of hydrogen tanks

Hydrogen storage system is a quite delicate matter in terms of safety. Gas explosion characteristics are well known, and so particular attention must be considered when managing parts of the hydrogen system. Storage tank is the most important component from safety point of view and is heavily regulated in UN R134. According to the rule, storage system is composed of:

- Storage container: hydrogen tank.
- TPRD: thermally-activated pressure relief device, if temperature overcome a threshold this valve is automatically opened, and gas is expelled to environment.
- Check valve: this valve is connected to the fuel line to the vehicle. It has the role of preventing reverse flow of gas.
- Automatic shut-off valve: it blocks the flow to fuel cell in emergency situation.

Hydrogen storage systems must have all these components directly mounted and ensure service life of at least 15 years.

In order to be approved and homologated, tanks must pass a series of tests:

- Tests for baseline metrics: first test is performed by hydraulically pressurize three identical tanks until burst. Explosion pressure must be at least 225 per cent of NWP (nominal working pressure). Second test is performed with three containers pressure cycled at 125 per cent of NWP. No leakage must be seen for at least 22000 cycles.
- Tests for performance durability: this is a series of verifications done in series on the same tank and it should not leak to be approved. First test is proof pressure where it is pressurized at 150 per cent NWP and held for 30 seconds. Then drop test is performed by let the storage system to fall on ground from several angles. Surface damage test is performed by performing saw cuts of around 1 mm depth on container in search of leaks and then with a cutting pendulum 5 slots are

created. Then chemical exposure test is performed by applying to those 5 areas 5 different chemicals that are common in road environment. Used solutions contain sulphuric acid (battery acid), gasoline, ammonium nitrate (urea) and others. To pass this test container must be pressure cycled at 125 per cent NWP for many cycles. Temperature test is done at high pressure keeping at least at 85° C for more than 1000 hours. Then is also tested at medium pressure at $<-40°C$ and $>85°C$ for some cycles. After all this procedure it is pressurized at 180 per cent NWP and held 4 min. If does not burst, it has to be pressurized until burst. Final requirement is in fact that burst pressure is at least 80% of initial burst pressure.

- Tests for on-road performance: hydrogen is used to perform various pressure cycles. It is filled at many different temperatures and pressures. After every cycle is crucial that the system does not leak more than 46 ml/hr/l. Then the tank undergoes another pressure proof test at 180 per cent of NWP and a final burst like in previous tests.
- Test for service terminating pressure in fire: container is filled with hydrogen at NWP and placed in fire, temperature activated pressure relief device will have to release hydrogen in controlled way.
- Primary closure devices approval: TPRD must meet some performance requirements. For instance, pressure cycling is done, temperature and chemical resistance is assessed. Drop and vibration tests are done or also leak tests. Similar procedure is performed on both check valve and shut-off valve. All these components must be approved singularly so that their assembly is safe.

If the system is approved it must be labelled permanently with all information as serial number, NWP, type of fuel, and others. For each produced batch of maximum 200 tanks, one has mandatorily to pass a shorter testing procedure that ensure conformity of all containers with respect to original approved system.

Tanks arrive to the plant already approved and tested. They are already assembled with various required valves and the connection already tested. An option could be to perform a testing procedure prior their assembly in vehicle as it happens for CNG. All the system is in fact tested also after the final assembly in purge & leak procedure so it could be avoided. Tanks have to pass only a first visual inspection to be sure of absence of travel damages. Containers arrive from supplier filled only with 5 bar of nitrogen. Since tank is very resistant to temperature and external agents there are not present any particular shipping and storage requirements. Only important thing is to avoid any damage to the tank that could impact the container performance and durability. When tank has to be assembled is taken from warehouse and directly mounted to form subassemblies. It is enriched with a metallic structural frame and first connections are added to valves. At this point we have 4 subassemblies:

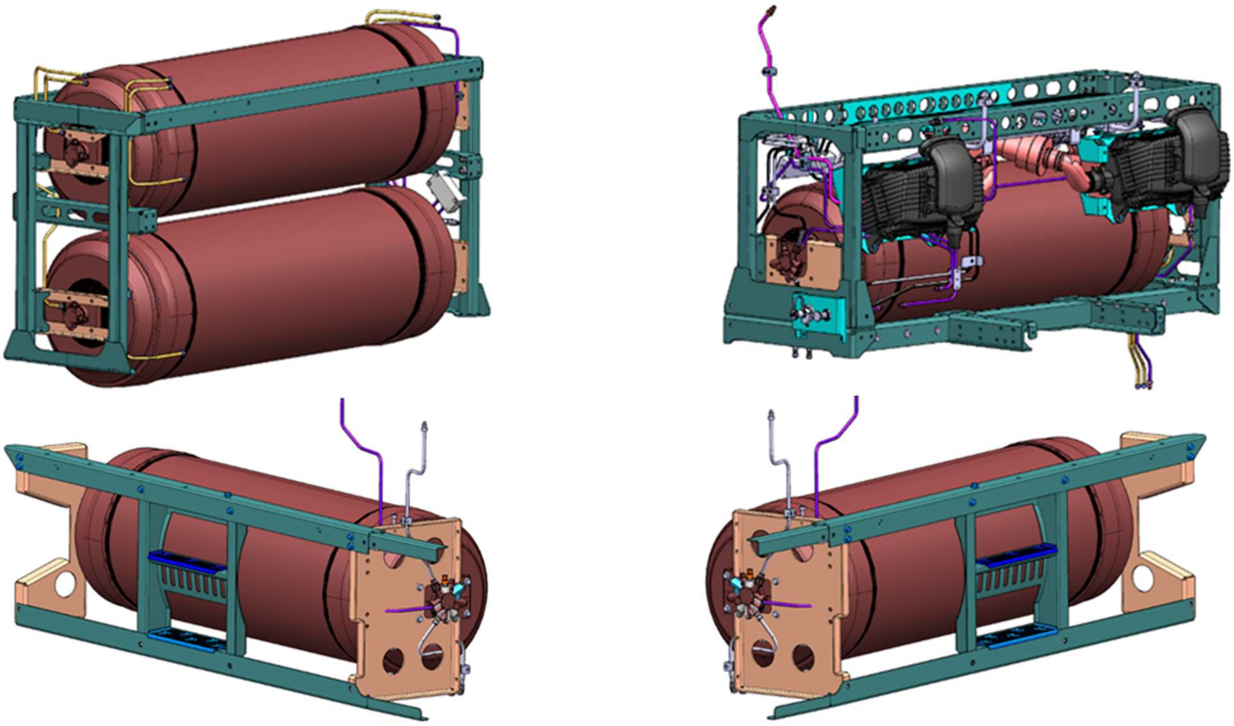


Figure 8.5 – Tested Sub-assemblies

- Lower backpack: dimensions: 1406x2316x1731mm; estimated weight: 250 kg;
- Upper backpack: dimensions: 662x2177x1262mm; estimated weight: 400 kg;
- Right side tank: dimensions: 747x2620x1095mm; estimated weight: 200 kg;
- Left Side Tank: dimensions: 747x2620x1095mm; estimated weight: 200 kg.

Since tank connections are very difficult to access when vehicle is fully assembled, best solution is to perform preliminary leak tests for these subassemblies. Since the tanks are tested and ensured from supplier as well as pipes, aim of test is to find problems and errors in connections and so the tanks valves are maintained closed. At least two paths can be followed for this procedure. An option could be to have a test similar to final vehicle leak test, another could be to have vacuum chamber test. First solution is to have gross leak check at 50 bar with nitrogen, followed by resistance check at 910 bar with helium, finished by sniffing with 700 bar. This procedure works exactly as it happens for final vehicle testing and so has downside to be very dependent on human errors. Second solution allows to accurately measure amount of leaking gas. Subassemblies, one at a time, are placed into a big metallic chamber and connected to an inlet and an outlet pipe. Then the door

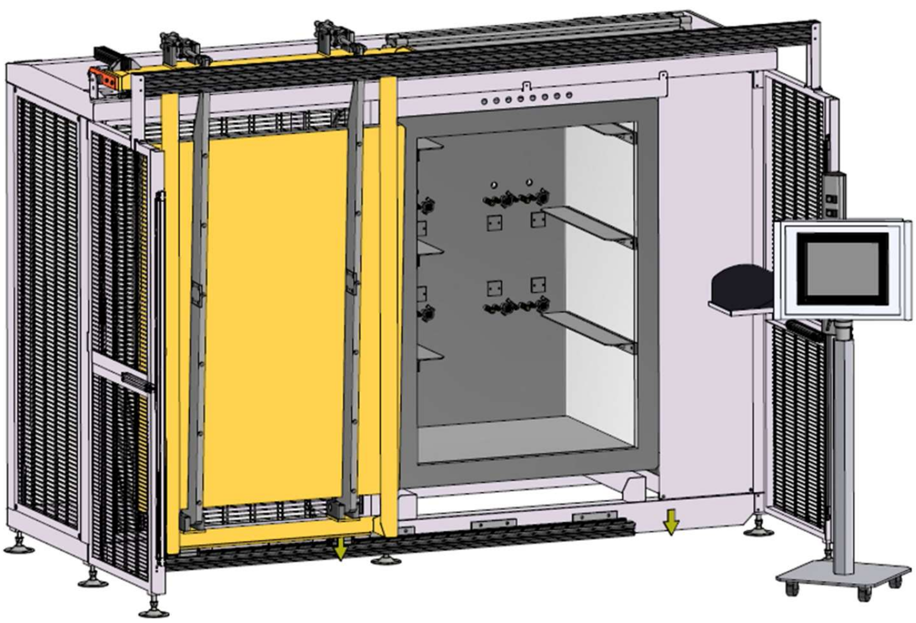


Figure 8.6 - Vacuum Chamber for leak test

is closed, and vacuum pump starts to suck all the air present in chamber until reaching a pressure of 10 mbar. At this point gross leak test with nitrogen and high-pressure leak test with helium is performed as in previous solution. Only difference is that is possible to spot any leak by measuring amount of helium in vacuum. In this way a precise quantitative result is got but is not possible to find the source of escape. For this reason, if a piece fails the test, a sniffing test at 700 bar is manually performed in order to find and consequently substitute the leaking component. The entire testing procedure for all 4 subassemblies requires around 60 minutes, so about 15 minutes each. For charging and discharging operations a particular trolley is used that is able to lift and pose subassemblies entering into the chamber. For this operation 5 min for each part is considered, leading to a total cycle time of around 80 min.

With this preliminary test is possible to reduce final leak test inspection points and dramatically increase safety of the product. In addition, if a leak is spotted prior the final assembly, vehicle rework activities are much reduced.

8.3. Safety considerations

Safety of the manufacturing process for FCEV truck is ensured mainly by involving the gas as late as possible. Hydrogen leads to many hazards which are mainly related to flammability.

Hydrogen is the element most present in nature, where is found mainly in form of water. Hydrogen gas H2 is composed by two atoms made of one proton and one electron each. For this reason, hydrogen is the simplest and smallest element. Gas is odorless, tasteless, and non-toxic. Humans are not in fact able to sense H2 and so particular care must be considered. There is some research with aim of adding odor to the gas as it is done for CNG but for now it is not achieved. It is 14 times lighter than air and so has the tendency to quickly disperse to the atmosphere. That is why it has the tendency to generate gas pockets below indoor ceilings. The simplicity of this gas is what makes it very easy to ignite. In flammability concentrations it can start burning even with a small static spark, it in fact requires 1/10 of energy for methane. Hydrogen gas needs oxygen in order to burn but is flammable in a very large concentration range. LEL is just around 4% and UEL is 77%. Lower limit imposes very high attention when dealing with gas in closed structures. Hydrogen has very low viscosity so 4% concentrations are quite easy and fast to be reached. When used at high pressures (as it happens for this truck), hydrogen has the tendency to auto-ignite directly from the leak. This gas produces an invisible flame. Humans, in fact, cannot sense anything related to this gas. The reason is that it emits very low infrared radiations that lead also to not be detected as heat. It however produces a lot of ultraviolet radiations and so can be easily sensed with sensors. Due to its small dimensions, the gas tends to permeate material and embrittle it. This is adding requirements for materials used for storage and piping that have to withstand high pressures and also be made of particular materials resistant to gas embrittlement.

Hydrogen characteristics are the cause of very strict regulations on the entire vehicle systems. Requirements and testing procedure of the containers has already been treated but UN R134 gives indications also on entire vehicle piping system. This regulation is crucial in order to ensure safety of the vehicle when hydrogen is on board. For what concerns the manufacturing process this situation happens only at the end where testing is performed with hydrogen or for reworking operations. Homologation of all the components is required and this should ensure safety of the entire system, that is further assessed with end of line vehicle testing procedure. Following regulations imposes to have various devices on vehicle as the pressure relief system which must be able to rapidly vent hydrogen out of the storage system. Venting pipe should be directed upward and away from possible ignition sources as electrical components. It must be placed away from enclosed spaces in order to avoid any possible gas accumulation. Vehicle exhaust system must not have more than 4% of hydrogen concentration during normal operation and never go above 8%. As already introduced in previous chapter, is crucial to avoid any hydrogen leakage to get into the cabin. Passenger compartment can in fact easily have sources of ignition as for instance human activities or electric failures. If any breakdown occurs on the hydrogen system, and more than 3% volume concentration is measured by cabin sensor, a warning signal must be provided to driver. At 4% the main shut-off valve of the system must be closed to isolate storage system from distribution one. Regulation also imposes position of storage system to be inward to the vehicle in order to avoid big damages in crashes. If accident provokes fire, venting system must immediately expel completely the stored hydrogen.

All these considerations are true given that the vehicle is operating outdoor, when hydrogen is indoor, many problems arise. Since hazards and countermeasures are very important for indoor presence of hydrogen, for the FCEV manufacturing process has been chosen to avoid gas involvement until the end when vehicle is safe and ready to be delivered. As already exposed in process paragraph, hydrogen tanks are assembled already tested and filled with nitrogen which is very safe. Vehicle testing is performed with nitrogen and helium and so no risks are present. First involvement of hydrogen is only after vehicle compliance assessment and is when purge and filling is performed.

Problem of hydrogen in closed spaces cannot however be eliminated when dealing with reworks and repairs (also in service centers). First thing to consider is always if it is necessary to place hydrogen systems indoor or if the operation could be performed outside where hazards are much reduced. Minimization of gas pressure should be performed, if possible, as well as the gas stored amount. Building should be equipped with several vents, in particular on the roof where possible accumulations are expected. If a leak occurs in closed building, it could immediately ignite or accumulate until reaching LFL. Main hazards are related to fire risk and asphyxiation. Problem is that hydrogen fire is invisible as well as leaks. For this reason, is crucial to have passive and active ventilation which must be paired with correct leak and fire detection system. Safety of the facility is enhanced with various kinds of sensors that must follow detection sequence: leak, concentration, and flame. First kind of sensors is in fact able to "listen" to high pressure leaks which generate ultrasonic noise. Ultrasonic gas leak sensors works only if high pressure hydrogen leaks (like this vehicle) and so can provide an early signal to people in building that a leak is present. Sensor works also in noisy environment such as a production plant since frequencies that it senses are much higher. Concentration is measured with several sensors in the building where each one monitors a single spot. Point detection can be made with catalytic bead sensors or with electrochemical sensors. This detection system is able to provide information of hydrogen concentration in enclosed environment and so to prevent fire (reach of LFL). Is crucial to place this kind of sensor close to the possible leak position since it is able to sense only small portion of environment. If leak starts to burn, flame detection sensors must be used. Hydrogen flame is invisible since produces UV and IR rays. Effective sensors involve both technologies but can sense other sources and provide false alarms. Another technology is called multi-IR, which analyzes various IR waves and is able to understand the actual presence of H2 flame by processing response to various frequencies.

Best practice is so to have all three kinds of sensors placed in correct position that activate alarms and ventilation system.

9. WCM

World Class Manufacturing is a business philosophy which is applied to industrial applications which results in an optimization and continuous improvement of manufacturing process. Main focus of WCM is the client, process is guided just by "pull" strategy and so by customer orders. Goal of this program is to optimize processes and reduce waste by increasing quality. This methodology does not however focus just on manufacturing process specifically but involves also matters which are around it. In fact, WCM comprises also safety, environment, maintenance, quality, logistics. Aim is to have zero defects, zero customer unsatisfaction, zero injuries, zero inventory, zero breakdowns and zero waste. Application of the WCM principles does not only involve company's management people, but everyone at every level is also in charge of finding waste or opportunities for improvements.

WCM is based on 10 pillars:

1. Safety – Workplace safety and ergonomics.
2. Cost Deployment – Economical loss sources.
3. Focus Improvement – logical thinking and problem solving.
4. Autonomous Maintenance –Direct worker maintenance.
5. Professional Maintenance – Professional maintenance.
6. Quality Control.
7. Logistics / Customer Services.
8. Early Equipment Management / Early Product Management – management of equipment and product possible problems early in development phase.
9. Environment.
10. People Development – Development of individual skills.

9.1. EEM

In this section Early Equipment Management is explained since it is the methodology which has been applied to the development of an innovative product and process as the one analyzed in this paper. This methodology is in fact very useful when new process has to be designed or modifications have to be performed. Purpose of EEM is to have safe equipment, lower LCC (life-cycle cost), short ramp up times, reliability, and maintainability.

EEM is in practice a tool for project management and is divided in different steps. In EEM three possible approaches are present: reactive (having a defect you then try to solve), preventive (try to prevent the error which could create a defect), proactive (understand the cause of a possible defect). First steps of this methodology are based on proactive approach in order to try and reduce possible future failures in process. In following steps, preventive and then reactive are used, always reminding that the later a fault is found, the higher will be total cost. For this reason, main goal of EEM is to anticipate problems to first phases of process development with goal of Maintenance Prevention. MP target is creation of a database of already demonstrated solutions to problems occurred in equipment lifetime. Sources are all the machinery of the company which is already in production and the solutions found in development phases (EEM). Practical tool used to perform this activity is the MP Info. When a problem is found, solutions are proposed and tested. If satisfying countermeasure is found, responsible will create a MP Info and submit it to EEM team. At this point the team reviews it and adds at least one question in a list. Checklists are in fact present at the end of each EEM phase in the design review process and are crucial to check if everything has been considered during development. In particular, is important that any failure occurred in the past is not repeated and possible future breakdowns are tried to be avoided.

EEM is composed of 7 phases:

STEP 1. Planning: Basing on company strategy, product investigation and benefit analysis are carried out to plan a new project. Team is started to be composed to be cross-functional, and analysis of required skills is performed. Volumes and resources needed are defined in order to predict required investment. Macro stages of the project are defined in a basic flowchart with milestones and objective.

STEP 2. Basic design: At this point the team is completed with specific roles and responsibilities. Product technical specifications are given at this point even if not definitive. With them is possible to understand suppliers' requirement and start to compare them. This is done by definition of technical specifications for bidding request. Data analysis is performed with various tools: MP info, QA-Matrix, PFMEA, KAIZENs, Risk Assessment. Quality Assurance Matrix is a table in which is possible to see how defects are generated. In particular is possible to see which processes' equipment and methods are faulty. Process Failure Modes and Effects Analysis is a methodology used to predict what could go wrong in equipment operation. In each process phase a series of possible failure is listed and scores are assigned to failure severity and probability.

Basic manufacturing plant layout is developed with clear objective of travel distances minimization. Training program is generated in this step for employees and suppliers.

STEP 3. Detailed design: Activities at this step are similar to the previous one, but big difference is that this time we have to go really in depth. QA design is performed trying to design equipment which realizes since from start defect free products. Basing on experience (MP Info) and simulations, design of process is performed with many objectives in mind. Design must be made for safety, reliability, quality, maintainability, AM, diagnosis. When design moves forward, PFMEA is continued to be performed. At the end the equipment design and plant layout are finalized.

STEP 4. Manufacturing: production of equipment is performed at this point, usually at supplier’s workshop. Final verification is performed for quality, safety, and performances. Site preparation is completed in parallel and must be ready for equipment delivery. Training of suppliers and of maintenance team are given.

STEP 5. Installation: Equipment is installed, and verifications are completed. Maintenance programs are finally specified, and opportunities of time reduction are searched. Definition of AM and PM plans goes on with spare parts list formalization.

STEP 6. Trial run: Equipment is tried in order to assess its compliance with features and targets defined in technical specifications document. Process parameters are measured and same is done for cycle time and capacity (Cp-Cpk). Also, materials and energy consumption have to be checked.

STEP 7. Initial flow: Equipment starts its production at regular pace and many parameters are monitored: capacity, defective rate, breakdowns, OEE. Particular focus is made on calculation of LCC by using real measured data, in order to really understand what was the effective cost of the equipment. Finally, project performances are evaluated in terms of costs and in terms of promptness of variations introduction.

9.2. PFMEA

Process Failure Modes and Effect Analysis is a tool designed to identify and prevent errors in the manufacturing process. It is divided in phases and a code is given to each one of them. Each phase is composed by various microphases that have to be followed in order, having each some specific requirements. For instance, if a wheel has to be mounted, two phases could be: positioning of the wheel and fastening to the hub. First phase could have as requirement the picking and lifting of wheel, positioning on the hub. Second phase could have as requirements to pick correct nut, pick pneumatic screwdriver, position nuts, tighten each nut. Each phase can have several failure modes and each failure may have several effects. Each effect may have also different causes and so finally the PFMEA can be seen as a tree structure. Each cause has its prevention possibility and detectability and finally a recommended action with a responsible. PFMEA works with a system of scores.

Severity Rankings

Ranking	Effect	Design FMEA Severity	Process FMEA Severity
10	Hazardous-no warning	affects safe operation without warning	may endanger machine or operator without warning
9	Hazardous- w/ warning	affects safe operation with warning	may endanger machine or operator with warning
8	Very High	makes product inoperable	major disruption in operations (100% scrap)
7	High	makes product operable at reduced performance (customer dissatisfaction)	minor disruption in operations (may require sorting and some scrap)
6	Moderate	results in customer discomfort	minor disruption in operations (no sorting but some scrap)
5	Low	results in comfort and convenience at a reduced level	minor disruption in operations (portion may require rework)
4	Very Low	results in dissatisfication by most customers.	minor disruption in operations (some sorting and portion may require rework)
3	Minor	results in dissatisfication by average customer.	minor disruption (some rework but little affect on production rate)
2	Very Minor	results in dissatisfication by few customers.	minor disruption (minimal affect on production rate)
1	None	No effect	No effect

Detection Rankings

Ranking	Effect	Design FMEA Detection	Process FMEA Detection
10	Absolute uncertainty	No chance that design control will detect cause mechanism and subsequent failure.	No known process control to detect cause mechanism and subsequent failure.
9	Very remote	Very remote chance that design control will detect cause mechanism and subsequent failure.	
8	Remote	Remote chance that design control will detect cause mechanism and subsequent failure.	Remote chance that process control to detect cause mechanism and subsequent failure.
7	Very Low	Very low chance that design control will detect cause mechanism and subsequent failure.	
6	Low	Low chance that design control will detect cause mechanism and subsequent failure.	Low chance that process control to detect cause mechanism and subsequent failure.
5	Moderate	Moderate chance that design control will detect cause mechanism and subsequent failure.	
4	Moderately High	Moderately high chance that design control will detect cause mechanism and subsequent failure.	
3	High	very remote chance that design control will detect cause mechanism and subsequent failure.	High chance that process control to detect cause mechanism and subsequent failure.
2	Very High	Very high chance that design control will detect cause mechanism and subsequent failure.	
1	Almost Certain	Design control will almost certainly detect cause mechanism and subsequent failure.	Current control almost certain to detect cause mechanism and failure mode.

Occurrence Rankings

Ranking	Effect	Failure Rates	Percent Defective	Cpk
10	Extremely High	> 1 in 2	50%	Cpk < 0.33
9	Very High	1 in 3	33%	Cpk ~ 0.5
8	Very High	1 in 8	10-15%	Cpk ~ 0.75
7	High	1 in 20	5%	
6	Marginal	1 in 100	1%	
5	Marginal	1 in 400	0.25%	Cpk ~ 1
4	Unlikely	1 in 2000	0.05%	
3	Low	1 in 15,000	0.007%	Cpk > 1.33
2	Very Low	1 in 150,000	0.0007%	Cpk > 1.5
1	Remote	< 1 in 1,500,000	0.000007%	Cpk > 1.67

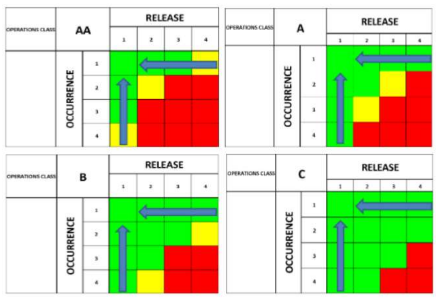


Table 9.1 - PFMEA scoring method and O&R tables

Three considered parameters are severity, detection, and occurrence. Severity score is assigned to each effect basing on its potential harm on people or damage to equipment. Occurrence ranking is given to each cause basing on the number of times or pieces affected by failure. Detection score is given considering if the designed process control is able to detect cause of a failure. This parameter is also called release since it specifies how much is the process control able to avoid releasing defective pieces. First two parameters have increasing scores which follow increasing damages (S=10, O=10; means very bad failure with extremely high occurrence). On the other hand, detection parameter has opposite trend: the more I am able to detect a cause of defect, the lower is the score.

At the end these three scores are multiplied in order to get Risk Priority Number:

$$R.P.N. = S \times O \times D$$

RPN is considered low if below 50, medium if below 100, high if below 150, very high if above 200. Low risk does not usually require any attention, starting from medium a recommended action must be proposed. Usually, corrective activities are performed on occurrence and then on detection. Severity never changes. After it is implemented, new evaluation of the RPN is made and improvements are measured. Final RPN must be always in low-risk area or exceptionally in medium range.

Results of PFMEA can be schematized in O&R table. For this tool, each failure is classified basing on the effect that could have on final client:

- AA: components which could impact safety of customer. Usually homologated.
- A: Functionality defects which do not impact safety.
- B: Aesthetic defects.
- C: Defects which could interfere with assembly operations.

Each failure's score is placed in the table and so it becomes very straightforward to understand general status of the failure prevention. For each class one table is compiled in original and modified state. In this way is also easy to understand the effect of proposed improvements. It is quite obvious that at final stage all the potential failures must be in green zone. Color zones are not equal for every class:

for AA failures is obvious that less acceptance is required and so the red zone is much bigger with respect to C defects.

This tool has been widely used to prevent failures in assembly of new components as those related to electric vehicle. The analysis has been performed on each of the most important assembly phases and, as an example, the PFMEA made for electrical high voltage harness is considered. In particular, just a small part of the entire examination has been selected in order to show some different operations performed during harness assembly.

This part of the process is composed of four consecutive operations:

- 320: Pick bracket, screws and nuts and tighten on chassis. Performed with pneumatic screwdriver.
- 330: Put back to side the pneumatic screwdriver.
- 340: Pick up wiring and set it on the chassis.
- 350: Perform connections with PDU and check them.

For the first operation some not serious failures could be mis-picking of pieces, or difficulties in placing bolts in correct position. A possible failure could be the picking of wrong screws due to the presence of many variances at the workstation. This failure is reduced of score by acting on occurrence; in fact, by positioning and marking in a specific way the screws, is possible to hardly diminish the failure risk. Problem could arise from non-presence of screwdriver in station or its malfunctioning. These failures are avoided by providing a scheduled maintenance plan. Going into details, if screwdriver is not correctly calibrated, a severity score of 7 is given since it leads to minor disruption in operations. Concerning occurrence, a score of 3 is assigned due to its rare incidence. Finally, a 6 for detectability is considered, there is low chance of spotting the cause just by testing 1 piece every 10. At the end the RPN is 126 so high risk. Proposed action is to have a control schedule and to calibrate the tool every 15 days.

Ref. Dime	Process Function Requirement	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s)	Occur	Current Process Controls Prevention	Current Process Controls Detention	Detec	R.P.N.	Recommended Action(s)	Responsibility & Target Completion	Action Results: Action Taken	Sev	Occur	Det	R.P.N.
320	Pick from side line: - No1 BRACKET - No2 SCREWS - No2 NUTS set on chassis frame and tighten completely by pneumatic screwdriver.	Mispicking	Production loss	8		Missed supply	5	Detectability: visual inspection		2	80				0	0	0	0
		Screws wrong collection	Non-complying fastening	5		Different kinds of screws available	4	Proactive action: Visual / operation sheet, staff training		9	180	Goods recognition at side line	Logistics		5	2	9	90
		Bolts missing fitting	Production loss / Resume for repair	7		Screws thread filthy or damaged	4	Detectability: visual inspection		2	56							
				7		Bolts / holes center to center distance not compliant to drawing	4	Detectability: visual inspection		2	56							
		Failed screwing	Production loss	9		Screwdriver missing in work station	2	Detectability: visual inspection		3	54	Provide for scheduled maintenance plan as per standard. Provide for back-up tools	maintenance service / plant		1	8	3	24
				9		Malfunctioning screwdriver	2	Detectability: visual inspection		3	54				1	8	3	24
		Screwing out of torque range	Tightening loosening/functionality loss	7		Screwdriver not calibrated	3	Proactive action: Screwdrivers maintenance according to standard with management and check procedure of screwdrivers setting Detectability: Test 1 in 10 pieces		6	126	Control schedule / screwdriver torque calibration every 15 days	maintenance service / plant		1	8	5	40
				7		Screwdriver torque range unsuitable with tightening torque nominal value	3			8	168	Preemptive study for suitable screwdriver typology	Technologies department		1	8	5	40
330	Put back: - PNEUMATIC SCREWDRIVER to side line.	Missing storage	Production loss	8		Noncompliance to operation sheet	2	Proactive action: Visual / operation sheet, staff training		3	48							0
340	Pick: - No2 WIRINGS and set on chassis frame according the lay-out drawn. (2 OPERATORS)	Mispicking	Production loss	10		Missed supply	2	Detectability: visual inspection		1	20							0
		Unobserved wiring lay-out	Production loss / Resume for repair	9		Inadequate wiring lenght	3	Detectability: visual inspection		5	135	Provide marks along the wires lenght	Engineering		3	3	5	45
350	Perform wirings connection by - No2 QUICK CONNECTORS to front PDU. Check correct connection by means of extraction stress by hand.	Wiring connector missed coupling	Production loss / Resume for repair	9		Inadequate wiring lenght	3	Detectability: visual inspection		5	135	Provide marks along the wires lenght	Engineering		3	3	5	**45**
				8		Connector incorrectly connected	2	Proactive action: Visual / note on operation sheet for correct connection check, staff training		4	64							
				9		Procedure not performed by operator	2	Proactive action: Visual / operation sheet, staff training		2	36							
		Connector unsteady coupling		8		Damaged connectors	2	Detectability: visual inspection Proactive action: supply quality check		5	80							

Table 9.2 - PFMEA of HV Harness

Passing to the lay down operation of the HV harness on the chassis, main failure could come from the wrong cable length. Scores would be 9 (very dangerous and also product would not work), 3 (low occurrence) and 5 (through visual inspection you should spot the problem) leading to a score of 135. Proposed action is to provide marks along wires length, doing this the severity falls down to 3 and RPN falls in acceptable range. Final operation of connection could have failures related to incorrect or avoided connection by the operator. These are reduced by training staff. Another problem could arise if the connector is damaged, low risk is result of supply quality check and visual inspection.

10. Conclusions

This dissertation aims to detect and analyze all the differences that arise in manufacturing process of alternative fuel vehicles. In particular the study is focused on four kinds of propulsion systems applied to same vehicle. Work starts by comparing vehicles' characteristics in order to underline similarities and discrepancies. Is possible to spot many similarities of diesel with natural gas version, and of electric with hydrogen vehicle. Natural gas is a solution that provides substantial advantages with very small product variations. Main impact is on fuel storage which is no more at atmospheric pressure as for diesel, but is highly pressurized. This change leads to safety challenges related to gas tanks and piping. Every other component is however kept equal and so, from manufacturing point of view, is treated as a vehicle adaptation more than a new product. For what concerns battery electric truck, many product differences arise. Vehicle's main systems are converters, inverters, batteries, and e-axle. In this case a complete vehicle reengineering has been performed and only few parts have been carried over. Engine and driveshaft are no more present and at their place a new axle is mounted which integrates motors and drivetrain. Finally, fuel cell version of the truck shares powertrain and batteries with electric variant, but has completely different parts composing hydrogen system. Fuel tanks are very voluminous and heavy, they also require particular attention on safety aspects. They are connected to fuel cell with a sequence of pipes and valves. Fuel cell is placed in engine bay and produces electricity from hydrogen. This energy is stored in two battery packs to power the e-axle.

Analyzing the manufacturing processes differences has led to many distinctions from traditional vehicle. Starting with natural gas truck, main impacts are found in assembly shop, even if it is shared with diesel version. Changes in process are mostly related to fuel tanks. These components, for LNG and in particular for CNG, impose new requirements which lead to variations in subassembly preparations.

Tanks must be tested in search of leaks and must be assembled with safety valves. Their mounting on vehicle do not impose any new challenge. Main difference is found in end of line testing, where the vehicle must undergo a series of additional procedures in order to ensure its safety. In particular, main aim is to find leaks which could expel flammable and pollutant gas to environment.

Considering battery electric vehicle, differences are principally in assembly shop. This truck shares limited number of components with diesel version and so new assembly operations must be performed. Most important variation is however related to batteries. Accumulators are dangerous, bulky, and costly components which have to be correctly managed to ensure safety and quality of product. Prior their assembly, they must follow a precise testing procedure to assess their reliability and performances. Since the vehicle works with high voltage, many safety issues are present and so countermeasures have to be considered.

Hydrogen truck is produced together with electric vehicle and shares many operations. Differences are however present with all other variants starting from BIW. Cabin does in fact require additional work to ensure sealing from gas leaks. In assembly shop main impacts are on subassembly preparations. In particular hydrogen tanks have to be managed carefully and tested prior their mounting on vehicle. Another main implication is on final vehicle testing procedure which is longer and more complicated comparing to other versions. Since hydrogen involves risks of flammability and it is imperceptible, big attention is placed in ensuring that the produced truck is safe for customer. A series of test is performed on hydrogen system in search of failure and leaks. Impact is also on buildings since safety countermeasures have to be considered to reduce risks related to hydrogen escaping the vehicle.

All these main impacts clearly show that a switch toward cleaner vehicles is possible even if, in some cases, the production process is not straightforward. This work really provides an example showing how really is to industrialize alternative fuel vehicles and which are main challenges. This analysis is very important in order to assess real feasibility of production processes and to understand if today is possible to produce these kinds of trucks. Results show that natural gas introduces few issues in industrialization since the process remains mostly unchanged. This suggests a moderate effort in adapting diesel truck production into natural gas. Passing to electric truck, many differences arise in assembly process and substantial work has to be performed for new product production. This underlines that a switch toward electric trucks is not an easy matter from manufacturing point of view, but all the obstacles can be overcome. Hydrogen vehicle has greatest impact on production process. Variations affect many aspects of the production plant imposing completely new issues. After the analysis is clear that producing this kind of trucks is a completely different thing with respect to traditional vehicles. An almost complete process reassessment is required leaving this vehicle as the most inaccessible and complicated to be produced.

This work has clearly showed that today is possible to produce alternative fuel vehicles through process reengineering and adoption of new solutions. Even if industrialization of clean trucks sometimes presents big challenges, is conceivable and desirable that in future, clear and successful solutions will be present, leading to strong diffusion of zero pollution vehicles in the world.

11. List of Figures

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13. References

https://www.awe.gov.au/science-research/climate-change/climate-science/understanding-climate-change

https://www.nationalgeographic.org/encyclopedia/greenhouse-effect/

https://www.climate.gov/media/12885

http://www.sietitalia.org/wpsiet/WP%20SIET%202019_1%20-%20Danielis.pdf

https://www.ilsole24ore.com/art/emissioni-co2-arrivano-multe-ecco-case-penalizzate-e-quelle-piu-green-ADrRxV7

https://www.automobile.it/magazine/come-funziona/macchine-ibride-come-funzionano-1629

https://energyeducation.ca/encyclopedia/Liquefied_natural_gas

https://energyeducation.ca/encyclopedia/Compressed_natural_gas

https://afdc.energy.gov/vehicles/natural_gas.html

C. Amann, L. Bonderson, R. Herret: *"Alternative propulsion Systems Impact"*

J.E.Sinor: *"Comparison of CNG and LNG Technologies for Transportation Applications"*

https://www.snam.it/en/energy_transition/sustainable_mobility/compressed_natural_gas/

https://www.c2es.org/content/renewable-energy/#:~:text=Renewables%20made%20up%2017.1%20percent,come%20from%20wind%20and%20solar.

https://www.wired.co.uk/article/lithium-batteries-environment-impact

https://afdc.energy.gov/vehicles/fuel_cell.html

https://en.wikipedia.org/wiki/Fuel_cell

https://www.csagroup.org/store/product/CSA%20B51:19/

https://rmi.org/run-on-less-with-hydrogen-fuel-cells/

https://www.eia.gov/energyexplained/natural-gas/

https://www.federmetano.it/il-biometano/

https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5

https://us.sunpower.com/how-many-solar-panels-do-you-need-panel-size-and-output-factors

https://www.pwc.com/us/en/industries/industrial-products/library/electric-vehicles-charging-infrastructure.html

https://techcrunch.com/2021/09/19/how-to-meet-the-demand-of-ev-infrastructure-and-maintain-a-stable-grid/

https://h2me.eu/about/hydrogen-refuelling-infrastructure/

https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php

Yosho Mizutani, *"Pipe Shield High-Voltage Wiring Harness"*

https://www.amphenol-industrial.de/en/MSDXLM400/MSD-connector-with-400A-fuse/p7142

https://mozees.no/phd-blog-why-do-lithium-ion-batteries-catch-fire-or-explode/

https://encyclopedia.pub/3503

https://www.powerandcables.com/product/electrical-safety/insulating-gloves-lv-mv-hv-11kv-33kv-gloves/

https://www.grainger.com/know-how/safety/ppe-in-the-workplace/hand-protection/kh-electrical-gloves-5-things-to-know

https://www.flashbattery.tech/omologazione-ece-r100/

Deutsche Gesetzliche Unfallversicherung, "*DGUV 200-006*"

Comitato Elettrotecnico italiano, "*CEI 11-27*"

https://www.iangv.org/natural-gas-vehicles/naturally-safe/

Yangtao Liu, Ruihan Zhang, "*Current and future lithium-ion battery manufacturing"*

RWTH Aachen University: "*Production of Fuel Cell components"*

B. Fuster, *"GUIDELINES AND RECOMMENDATIONS FOR INDOOR USE OF FUEL CELLS AND HYDROGEN SYSTEMS"*

UNI EN ISO R134