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Cost efficient high power battery for Hybrid Power Pack destined for fuel cell powered heavy duty vehicles

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Executive Summary

Heavy Duty electric vehicles like ebuses and etrucks will widely use in the future a fuel cell power pack as a source of power. For proper operation of fuel cell, a high power li-ion battery is required to solve all start-stop issues of the fuel cell operation as well as providing regenerative braking function and increase a dynamics of the drive. For the current generation of heavy duty vehicles, the LTO battery is widely used due to its excellent power properties. However there are limitation in this technology as well as very high prices compared to LFP and NMC chemistries. Consideration of more cost efficient solution for power pack battery for fuel cell drive is presented in this paper.

Keywords: hydrogen, e-bus, electric bus, fuel cell, TCO

1 Introduction

Commercial viability of a city bus is inseparably linked with Total Cost of Ownership from operators perspective. Current market is changing rapidly for all types of buses, as purchase cost varies in BEVs due to shifting raw cell material costs and operation cost raises in ICEV as diesel prices increase due to climate change and ongoing conflicts. For FCEV we can see varying both initial and operation costs due to relatively low maturity of technology and developing hydrogen supply chain which brings many variables into the market.

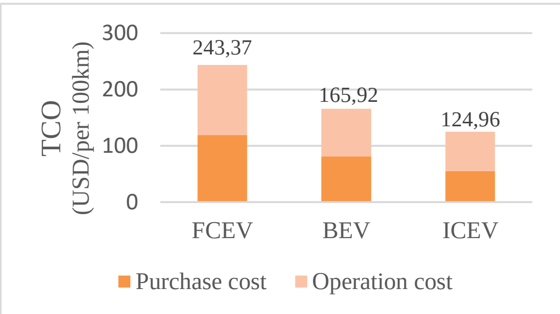


Figure 1: High level TCO for a bus breakdown (US, 2019)

Purchase cost of zero-emission bus is still higher than this of internal combustion one, mainly because of costs of energy storage and conversion system addition and components mark-up as NRE costs have to be reimbursed in newly developed components price. From current analysis purchase cost of average hydrogen bus is more than two times higher than this of a ICE bus and nearly 1,5 times this of a BEV. Important part of FC vehicle price, that differentiates it from this of BEV, is Hybrid Power Pack cost [1].

Its breakdown is estimated to look as presented in figure 2. As seen here, a fuel cell module is the most important cost factor, leaving battery far behind. This value is subject to used cell chemistry and amount of available energy, although it should not exceed 20% of Power Pack cost. It is important to acknowledge that the same thermal management system may be used for both fuel cell and battery control. From this, it is important to highlight that as costs of fuel cells are many times higher than those of battery systems, power pack integrators shall focus on matching those components with as low lifetime degradation of fuel cell as possible in mind.

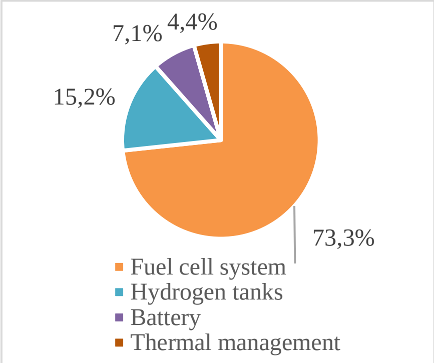


Figure 2: Hybrid Power Pack breakdown [1].

Operation cost depends highly on future hydrogen prices, oil prices and future CO2 emission taxes. If assuming similar maintenance prices per kilometer, crucial component is fuel cost. As of beginning of 2023, using publicly available prices, it is around $44/100km for ICEV and $83/100km for FCEV. Current estimations are for hydrogen prices to lower significantly to around $1,5/kg and diesel prices to rise to around $1,5/liter in next 5 years. Although, it is important to know, that those values are subject to significant risk of error.

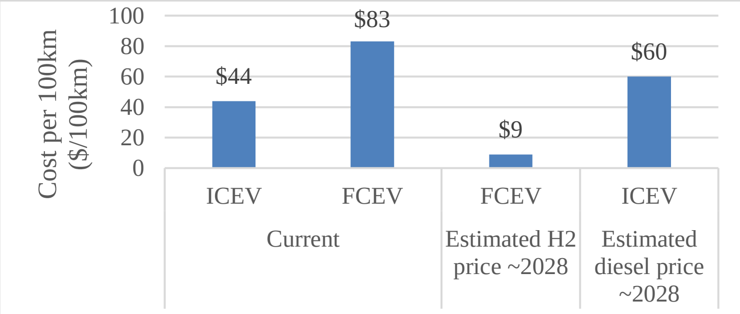


Figure 3: Operation costs predictions [1].

Table 1: Hydrogen bus examples of different OEMs.

Vehicle OEM	Alexander Dennis	Solaris	Solaris	VanHool	VanHool	Caetano	Autosan	PAK-PCE
Bus name	Enviro400 FCEV	Urbino 12	Urbino 18	A12	A18	H2.City Gold	Sancity 12LFH	NesoBus
Fuel Cell System	Ballard	Ballard	Ballard	Ballard	Ballard	Toyota	Confidential	Ballard
Energy storage system manufacturer	Impact (LTO)	Impact (LTO)	Impact (LTO)	Actia (LTO)	Akasol (NMC)	(LTO)	Impact (LTO)	Impact (LTO)
Bus length	11.1m (double decker)	12m	18m	12m	18 m	10,74m	12m	12m
Fuel Cell Module power	60 kW	70 kW	100 kW	70 kW	100 kW	60 kW	70 kW	70 kW
Battery energy	30 kWh	60 kWh	60 kWh	24 kWh	132 kWh	44 kWh	45 kWh	30 kWh

2 Hydrogen powertrain

Electric buses and hydrogen buses are both powered by electricity, but they differ in the way that energy is produced and stored. Electric buses use batteries that store electricity to drive the electric motor, while hydrogen buses use fuel cell technology where hydrogen and oxygen react with each other to create electricity that drives the engine, with the battery only providing a power buffer [2].

Table 2: Hydrogen bus and electric bus pros and cons.

	Bus with Hybrid Power Pack	Bus with Battery
Pro	- Vehicle range (for 18m bus its >350 km) - Refuelling in less than 20min - Plug-in to grid is not required - Storage of hydrogen does not require high costs	- High efficiency in conversion from renewable energy (~95%) - Mature technology with long battery lifetime (more than 8 years)
Con	- High cost (due to low scale) - Poor lifetime of Fuel Cell (~5 years) - Poor efficiency in conversion from renewable energy (~35%) - Refuelling infrastructure required - Difficulties in clean hydrogen availability	- Limited vehicle range - Long charging (limited availability of vehicles) - Charging infrastructure and management required

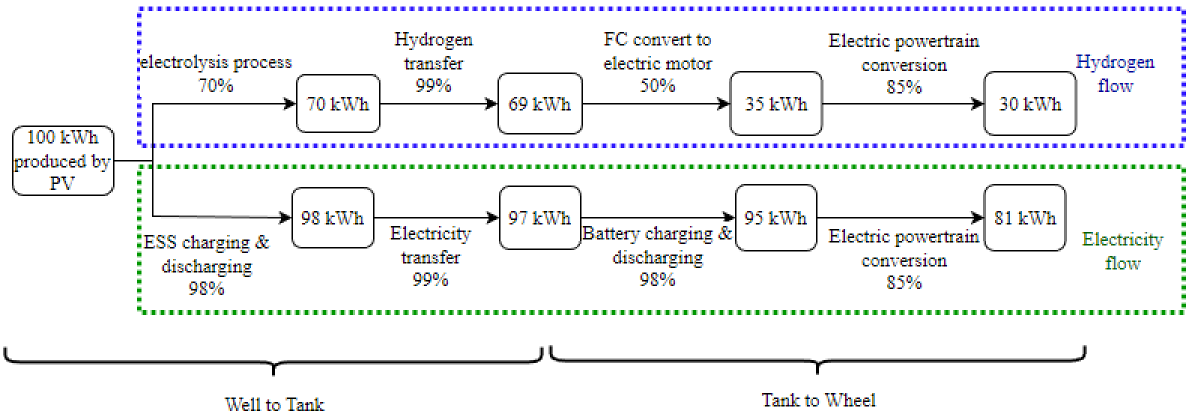


Figure 4: Well to Wheel analysis of hydrogen and electric bus with renewable energy source.

2.1 Hydrogen powertrain topology

The main difference between hydrogen and electric buses is that hydrogen buses have additional source of energy which is fuel cells that convert hydrogen into electricity, while electric buses are powered only by rechargeable batteries.

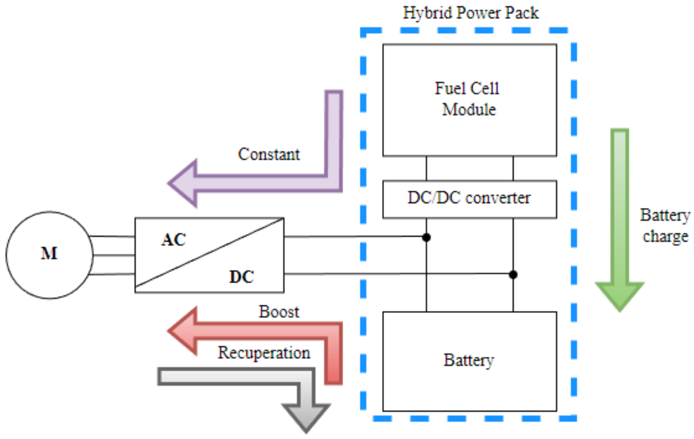


Figure 5: Topology of hydrogen vehicle power-pack.

In general, we can distinguish 4 paths of energy flow in the above drive:

- Constant power
- Boost
- Recuperation
- Battery Charge

One of the most important advantages of the battery over the fuel cell is the ability to immediately deliver maximum power, while the fuel cell has its own inertia and sometimes needs several seconds to start. Therefore, in the case of vehicles powered by a fuel cell, it is necessary to use a battery as a power buffer.

When the power required by the drive is greater than the power supplied by the fuel cell, the difference is provided by the battery. However, when the drive does not need power at the moment and the fuel cell is still working, then the battery is charged with excess power [3].

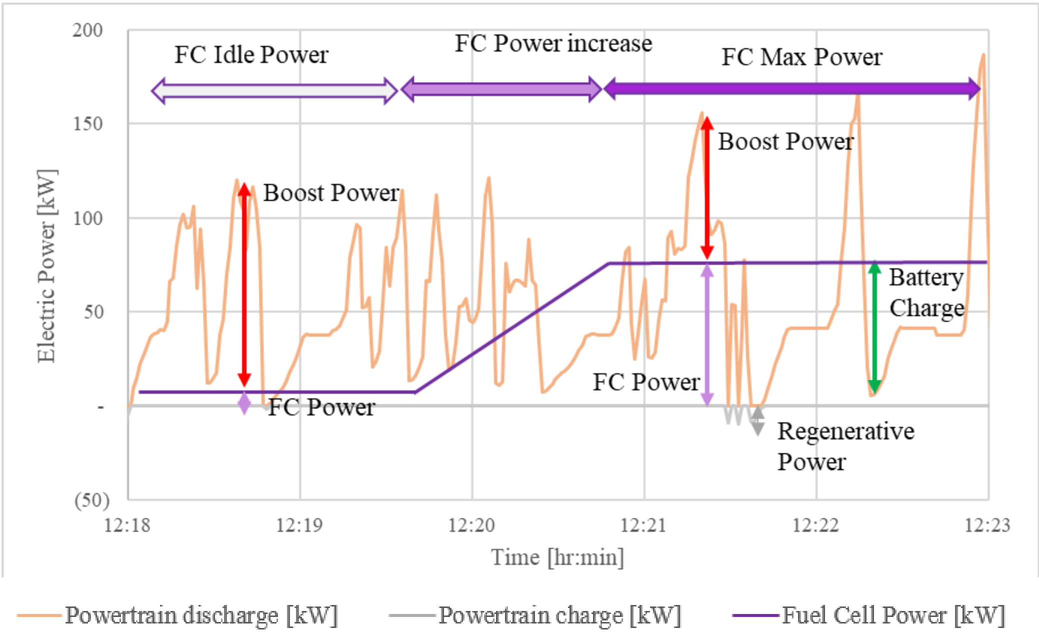


Figure 6: Example of power profile with energy flow explanation.

2.2 Powertrain selection methodology

This part of the article presents the hydrogen propulsion selection methodology that was used for the purposes of this publication.

Following assumptions has been taken into account during profile selection and analyse:

- Bus length 18m (powered by hydrogen fuel cell & battery)
- Daily Operation ~14h/day
- Daily milage 350 km
- Operation days 340 days/year
- Mileage ~120 000 km/year
- Fuel Cell to be shut down once a week (to prevent lifetime degradation)
- Fuel Cell idle power is not less than 15% of its maximum power

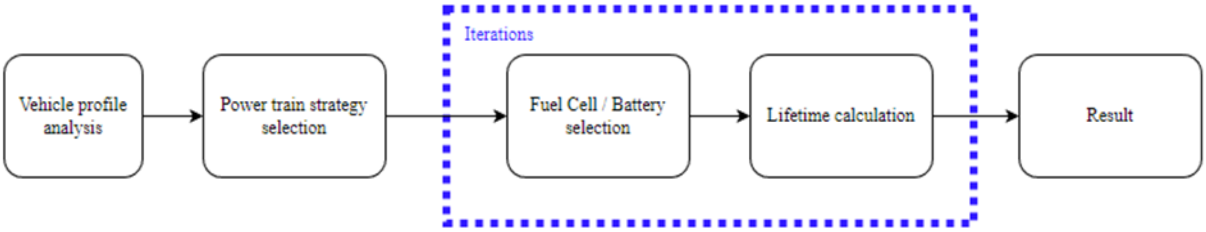


Figure 7: Methodology of powertrain selection.

2.2.1 Vehicle power analysis

As a first step, powertrain profile from the real vehicle has been selected. The profile is presented on the figure. From the power profile the most important parameter has been calculated and presented in following table.

Table 3: Crucial parameters of power profile.

Cycle parameter	Value	Unit
RMS during operation	75	kW
Cycle Energy discharge	730	kWh
Cycle energy charge (recuperation)	62	kWh
Peak discharge	316	kW
Peak charge	210	kW

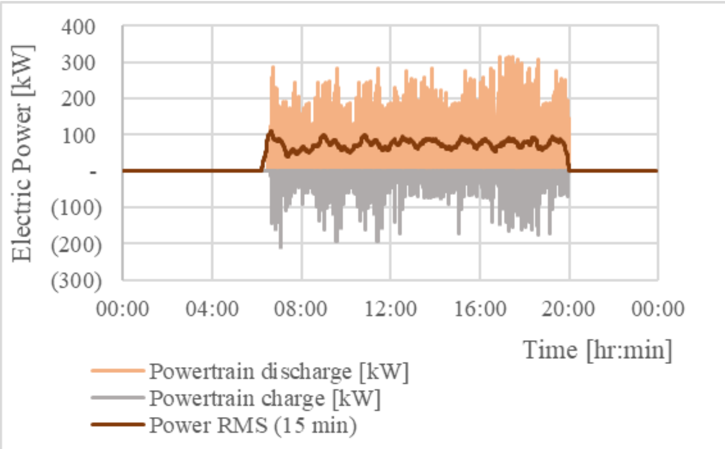


Figure 8: Daily power profile of the vehicle.

2.2.2 Powertrain strategy selection

It takes several approaches to plan fuel cell operation and each step is really important. However as the real strategies are quite complex, for purposes of this publication 3 simple strategies have been assumed and each one has been analysed during next steps. As it was mentioned above, the most cost critical component in the hydrogen vehicles is Fuel Cell Module, so one of the most important factors taken into account during the strategy selection is Fuel Cell preventions from degradation [5]. Therefore all three strategies focus on preventing excessive Start/Stop of Fuel Cell.

Strategy #1: Fuel Cell follow 1 min RMS, FC shut down once a week

In this strategy Fuel Cell follows RMS value of discharge power (discharge demand), than battery is discharged during bus operation and charged from fuel cell during non-operation (fuel cell is on idle power). In this strategy battery initial SOC and end SOC shall be on similar level in order to prevent overcharging in the next day.

Strategy #2: Fuel Cell Step Power, FC shut down once a week

Strategy 2 assume that Fuel Cell operate all week on idle power and provide maximum power when battery SOC is low and comes back to idle power when battery SOC is high enough. On the picture below desired SOC range has been set from 40% to 50%. In this strategy battery initial SOC and end SOC shall be on similar level in order to prevent battery overcharging in the next day.

Strategy #3: Fuel Cell Step Power, FC shut down once a day

In this case, the logic of the procedure is adequate to strategy number 2, except that the initial and final SOC do not have to coincide, because the fuel cell will turn off after the battery is charged (at the end of the shift).

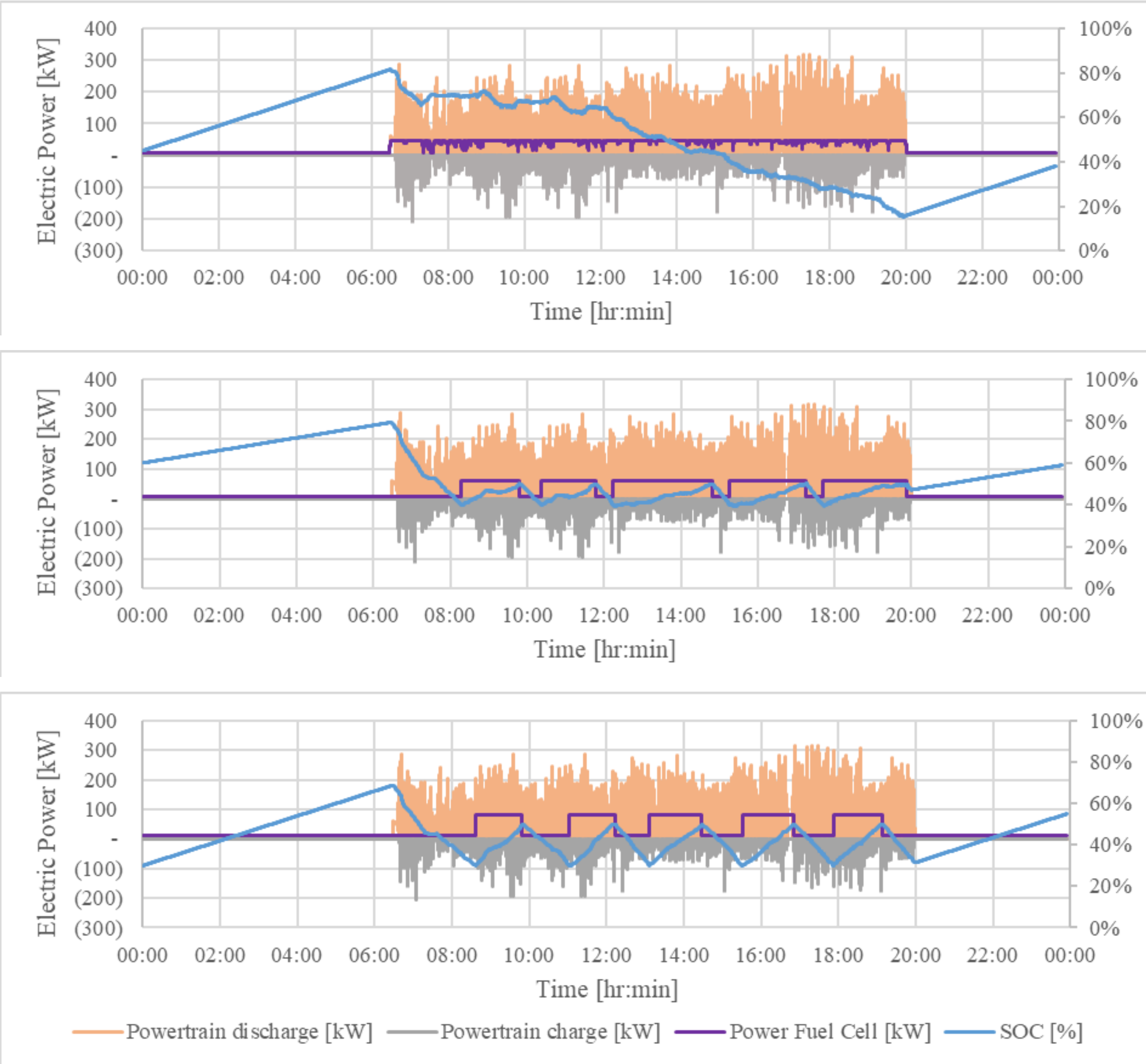


Figure 9: Power train strategies. Strategy #1 (up), Strategy #2 (middle), Strategy #3 (down).

2.2.3 Fuel Cell and Battery selection

In this step, Fuel Cell and Battery System must be selected. Main factors that can be moderated are:

- Maximum Power of Fuel Cell (it gives also idle power as 15% of maximum value)
- Installed energy of battery system
- Initial SOC of Battery
- Desired SOC operation range (for strategy #2 and #3 only)
- Maximum number of battery packs (space limitation)

Applying those factors, following output battery parameters has been considered in the next step:

- Profile of Battery (RMS, maximum C-rate, minimum C-rate)
- Battery energy discharge per day
- Battery Depth of Discharge (which gives minimum Usable energy in the End of Life)

Example for:

Strategy #3, where Fuel Cell has 80 kW of maximum power and 200 kWh of battery energy. Desired operation SOC range is from 30% to 50%. Maximum 2 battery packs can be placed in the vehicle.

Output power profile can be seen on Figure 10.

- RMS 51.4 kW
- Max Charge 275 kW
- Max Discharge 304 kW
- Energy discharge per day 397 kWh (135 MWh per year)
- Minimum energy required 80kWh

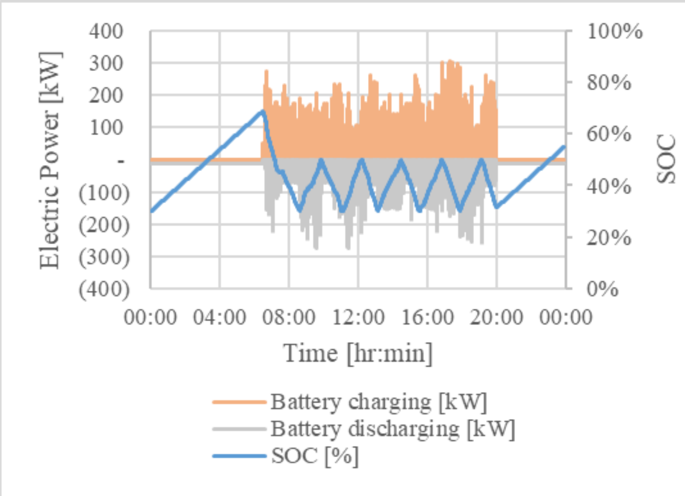


Figure 10: Example of profile after powertrain selection

2.2.4 Lifetime calculation

Taking into account moderated factors and output data from previous step, lifetime for different battery chemistries (NMC, LTO, LFP) must be done in order to calculated TCO.

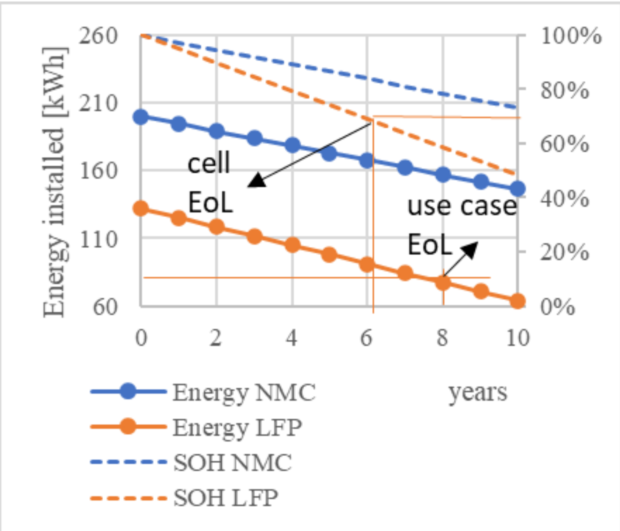


Figure 11: Example of lifetime calculation.

In this case definition of End of Life will come from following criteria:

- minimum possible SOH defined by cell producer (cell EoL)
- minimum SOH which allow to complete the battery profile (use case EoL)

Example of SOH calculation on the Figure 11. In case of 2 battery packs (LFP) with 120kWh installed energy, Eol coming from cell is 70%, which gives 6 years and EoL coming from use case is 80kWh, which gives 8 years. Lower values shall be considered. In case of 2 packs (NMC) with 200kWh installed energy, both EoL will be above 10 years.

3 Battery

The purpose of a Li-ion battery in a hydrogen vehicle is to store and manage the energy produced by the hydrogen fuel cell. The battery provides additional power to the vehicle during acceleration or when the fuel cell is not able to meet the demand, and also helps to capture energy during regenerative braking.

3.1 Cell chemistries

In heavy-duty vehicles there is no only one cell chemistry, which will cover all requirements gives my application specific, but up to know group of li-ion batteries is widely used in hydrogen buses.

Lithium-ion cells are a group of reversible (secondary) batteries that store energy electrochemically, in which:

- electrolyte is solution that enables lithium ion moving from anode to cathode,
- the anode is mainly graphite or less popular Li metal or oxides,
- the cathode is non-stoichiometric oxides or sulphides of transition metals with high voltage.

Currently, the following types of lithium cells are most commonly used in e-mobility industry (due to the chemical composition of the electrodes):

Table 4: Cell chemistry comparison [6].

	LTO	LFP	NMC
Cathode	LiNiMnCoO2	$LiFePO_4$	$LiNiMnCoO_2$
Anode	$Li_4Ti_5O_{12}$	graphite	graphite
Nominal voltage	~2.3 V	~3.2 V	~ 3.7 V

3.2 Battery packs for heavy-duty

As it was described in Introduction, most of OEM currently use LTO packs for hydrogen vehicles due to very high lifetime, which compensate high cost (than TCO is beneficial). However other chemistries shall be taken into account, when different fuel cell strategies and vehicle requirements are considered. On the following Figure, Roadmap of standard ICPT products has been presented.

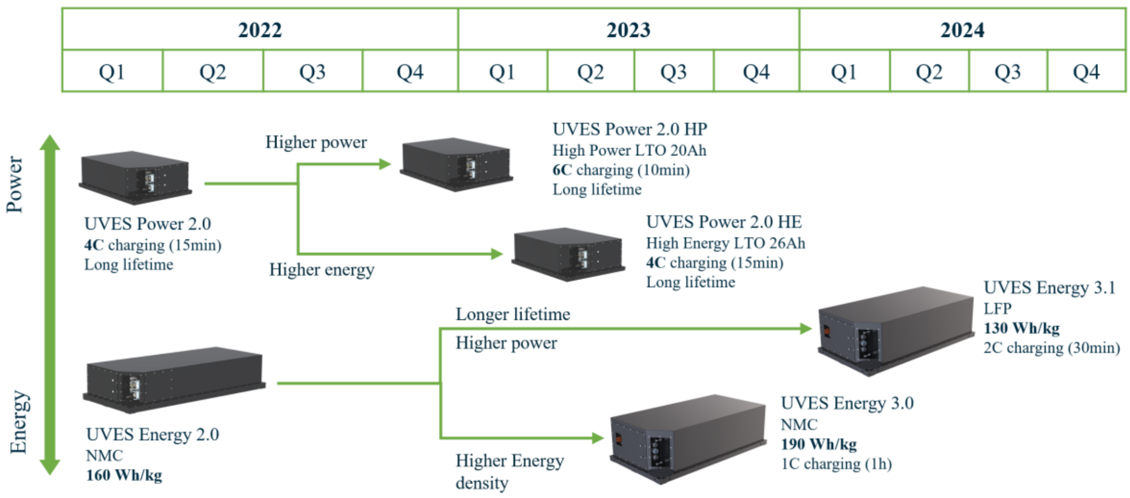
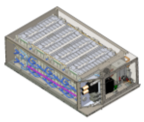
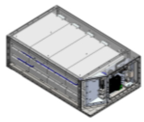
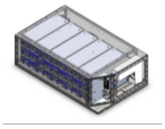


Figure 12: ICPT battery packs roadmap [7].

In the Table 5 top level parameters of 3 different chemistries has been presented, where LTO battery is available since 2021, NMC battery is available from this year (2023) and LFP is to be released in 2024. It is worth to underline, that all of packs presented in Table 5 have the same dimensions, operating voltage and main interfaces, which allow to use different chemistries in the same vehicle.

Table 5: Battery pack comparison. Crucial parameters.

Pack level parameters	**LTO**	**LFP**	**NMC**
Pack design			
Dimensions	L1350 mm x W800 mm x H410 mm		
Energy	30 kWh	60 kWh	100 kWh
Weight	500 kg	450 kg	525 kg
Energy density	60-70 Wh/kg	120-140 Wh/kg	180-200 Wh/kg
Lifetime	+++	++	++
Cost (per kWh)	100%	20%	25%
Raw material residual value	++	+	+++
	recycling profitable	recycling not profitable	recycling very profitable

LTO battery with the highest power performance has the lowest energy density, which makes this technology the heaviest with the lowest value of capacity in one battery pack. Power performance gives good opportunity to work as a power buffer for FCEV but because of the physical characteristics and difference in capacity compared to other chemistries it is the most expensive technology per kWh. On the other hand it's not just the single purchase that matters, so aim of the analysis is to present the TCO and impact of the lifetime in hybrid work for the chemistry where LTO chemistry leads.

Usual time for TCO calculation is 10 years of lifetime for the vehicle. LTO cells have a cycle life of up to >20,000 cycles. This is 4 times more than LFP and 10 times more than NMC. However, number of cycles shall not be taken in lifetime comparison, but energy throughput or energy discharged from battery up to End of Life, defined by cell or use case (what has been presented in section 2.2.4) .

Apart from TCO important matter is ESG and further usage of battery packs when they will end their life in hydrogen bus. The natural path is second life in energy industry where LTO is very good solution due to power performance. Third stage is recycling where LTO and NMC cells are much more profitable in recycling compared to LFP cells.

3.3 Roadmap of battery chemistries

Currently, lithium ion market is growing so fast. Cell's manufacturers are looking for solution that connect energy storage function of the battery and power performance. In Figure 13, the roadmap of the current and future the most popular lithium ion technologies are presented.

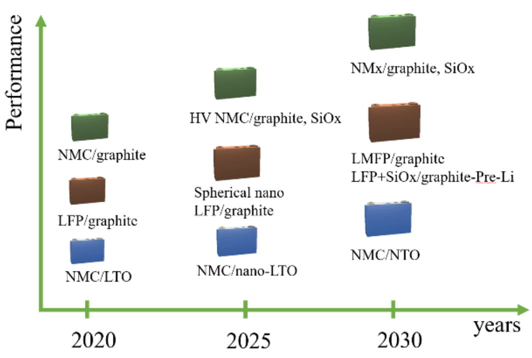


Figure 13: Cell chemistry roadmap.

Nowadays, LTO cell can be safely discharge up to 10 C. The application in fuel cell support, the LTO cell can deliver high peak power. It is determined by capacity of the each cell, type and manufacturer performance. As it can be seen in Figure 13, the performance of LTO cell is risen over time. Because of low energy density of this technology, the capacity of the commercial cells are improving. Also, in near future we can expect similar technology launched to the market. NTO is used nickel titanate oxide anode. It can bring higher energy density than LTO. Currently, there are a limited number of manufacturers production NTO and still, most of developing work shall be done.

There is also some examples that LFP lithium ion cells are adopted. This technology is known for their good thermal stability, long cycle life and high safety level. Also, it can deliver sufficient power performance with technology development. The most important grow is observed in energy density of the cell. Use of nanoparticles improves diffusion rate of ions within the cathode and allow better power performance of the cell. Also, it is known that there are improvement of anode material in case of power performance improvement [8].

In near future, NMC technology will improve their energy density because of implementing SiOx or additives as anode material. Also, commercialising the high voltage NMC cells with improved electrolyte can make huge different in energy density.

4 Results

In the Table 6 results from iteration described in Figure 7 has been presented.

Table 6: Results from powertrain selection.

Strategy		#1			#2			#3		
No. of use case		1	2	3	4	5	6	7	8	9
Powertrain Selection	FC power	45 kW	45 kW	45 kW	60 kW	60 kW	50 kW	80 kW	80 kW	120 kW
	Battery Chemistry	NMC	LFP	LTO	NMC	LFP	LTO	NMC	LFP	LTO
	Number of packs	2	2	3	2	3	4	2	2	2
	Battery energy	200 kWh	120 kWh	90 kWh	200 kWh	180 kWh	120 kWh	200 kWh	120 kWh	60 kWh
	Weight of battery	1050 kg	900 kg	1000 kg	1050 kg	1350 kg	2000 kg	1050 kg	900 kg	1000 kg
Power profile factors	Fuel Cell Average (24h)	28 kW	28 kW	28 kW	30 kW	31 kW	31 kW	32 kW	31 kW	32 kW
	Battery C-rate RMS	0.20 C	0.36 C	0.50 C	0.24 C	0.27 C	0.38 C	0.26 C	0.43 C	0.93 C
	Battery C-rate max	1.4 C	2.3 C	3 C	1.4 C	1.7 C	2.3 C	1.5 C	2.5 C	5 C
	Battery energy discharge (per year)	117 MWh	117 MWh	117 MWh	129 MWh	130 MWh	116 MWh	141 MWh	141 MWh	156 MWh
Lifetime	SOH after	88%	79%	94%	86%	87%	98%	84%	72%	91%

calculation	5 years									
	SOH after 10 years	77%	56%	88%	74%	74%	96%	67%	44%	83%
	Battery EoL after	8,5 years	4,5 years	>10 years	7 years	7 years	>10 years	6 years	3 years	>10 years
TCO	TCO per 5 years	0,09 USD/ km	0,10 USD/ km	0,14 USD/ km	0,09 USD/ km	0,08 USD/ km	0,29 USD/ km	0,09 USD/ km	0,10 USD/ km	0,14 USD/ km
	TCO per 10 years	0,09 USD/ km	0,08 USD/ km	0,07 USD/ km	0,09 USD/ km	0,08 USD/ km	0,14 USD/ km	0,09 USD/ km	0,10 USD/ km	0,07 USD/ km

TCO calculated in above table refer to battery system price, so TCO of Fuel Cell system shall be considered separately. TCO has been calculated assuming 120.000 km milage per year and battery change if lifetime was shorten than calculated period.

5 Summary

There is no only one cell chemistry for hydrogen vehicle. The choice of which chemistry to use depends on technical specific requirements for the vehicle, tender requirements, power profile, environmental conditions and strategy for fuel cell – battery configuration. The optimal solution for FCEV application is when fuel cell is not oversized. Oversizing leads to higher cost and more frequent shutdowns of fuel cell which ultimately affects lifetime. Currently, the most popular chemistry in commercial application for hydrogen bus is Lithium Titanate Oxide (LTO) especially because of power performance, robustness and the highest possible lifetime in cooperation with hydrogen fuel cell. The whole TCO calculation is related to lifetime vs initial cost vs number of exchanges (LCC cost) over the vehicle lifetime – the LTO battery gives the best economical solution with the lowest maintenance cost and highest quality at this moment. Over the years NMC and LFP are becoming more popular due to power performance and lifetime which can be competitive in the future for hydrogen application. In the finance perspective there is also safety and recycling aspect. This means that LTO can be more profitable than LFP and much more safe than NMC technology which is also calculated in development and production cost of the vehicle.

References

[1] Delloitte & Ballard, “Fueling the Future of Mobility. Hydrogen and fuel cell solutions for transportation.,” Shanghai, 2020.

[2] L. . Xu, J. . Hua, X. . Li, Q. . Meng, J. . Li and M. . Ouyang, “Control strategy optimization of a hybrid fuel cell vehicle with braking energy regeneration,” , 2008. [Online]. Available: http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.ieee-000004677674. [Accessed 3 4 2023].

[3] T. . Kojima, T. . Ishizu, T. . Horiba and M. . Yoshikawa, “Development of lithium-ion battery for fuel cell hybrid electric vehicle application,” *Journal of Power Sources,* vol. 189, no. 1, pp. 859-863, 2009.

[4] E. . Zakrisson, “The Effect of Start/Stop Strategy on PEM Fuel Cell Degradation Characteristics,” , 2011. [Online]. Available: http://publications.lib.chalmers.se/records/fulltext/144606.pdf. [Accessed 3 4

2023].

[5] T. . Horiba, “Lithium-Ion Battery Systems,” , 2014. [Online]. Available: https://ieeexplore.ieee.org/document/6816050. [Accessed 3 4 2023].

[6] Impact Clean Power Technology, “icpt.pl,” Impact Clean Power Technology, 02 2023. [Online]. Available: https://icpt.pl/e-mobilnosc/.

[7] S. . Jouanneau, Y. . Reynier, M. . Chami, W. . Porcher, L. . Daniel, F. . Fusalba and S. . Martinet, “Emphasis on LFP/LTO Li-Ion Technology: From the Material, Composite Electrode Design to Full Cell Behavior in Several Designs Including Bipolar Technology,” , 2010. [Online]. Available: http://ma.ecsdl.org/content/ma2010-02/11/1088.full.pdf. [Accessed 3 4 2023].

[8] F. . Sergi, L. . Andaloro, G. . Napoli, N. . Randazzo and V. . Antonucci, “Development and realization of a hydrogen range extender hybrid city bus,” *Journal of Power Sources*, vol. 250, no. 250, pp. 286-295, 2014.

6 Presenter Biography

Bartek Kras has been associated with e-mobility industry since 20 years. He is a specialist in designing and implementing Li-ion battery and fuel cell systems and has managed numerous projects in that field, carried out by the company since the beginning of its beginning. He is an author and coauthor of a numbers patents, trademarks and unique technical solutions in area of electromobility, Li-ion batteries, fuel cells and system control. He graduated from the Faculty of Electrical Engineering at the Warsaw University of Technology, where he also gained his Ph.D. title, and completed the ICAN Institute management study (Harvard Management Course).

Filip Jankun is a graduate of the Faculty of Mechatronics at the Warsaw University of Technology. He has over 14 years of experience in designing, developing and selling battery systems for transport. From the beginning of his career, he has been associated with Impact Clean Power Technology SA as a Product Manager, he was responsible for a number of ground breaking developments and implementations of innovative solutions in this industry. In the years 2020 - 2022 he was the Sales and Development Director responsible for global sales.

Artur Jagusiewicz is an experienced manager with strong technical background in embedded systems engineering, power electronics and energy storage in automotive industry. He has experience with development projects since 13 years which have resulted in commercial implementation and series production. He graduated Warsaw University of Technology in Electrical Engineering faculty and Warsaw School of Economics in Project Management faculty. Present position CTO in Impact Clean Power Technology with responsibility for R&D department.

Bartłomiej Mazan is leading a Technical Concept Team in ICPT. He is responsible for product development (battery systems for heavy-duty) and li-ion cell validation. He has been graduated on Warsaw University of Technology in Mechatronics. Currently is proceeding implementation doctorate in battery field. Involved in battery cell research since 2018.