

Direct Hydrogen PEM Fuel Cell Powertrain Manufacturing Cost Analysis for Automotive Applications

2023 Fuel Cell Seminar



Yong Yang, President
February 8, 2023

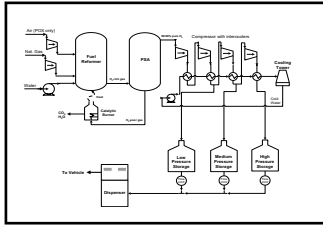
Austin Power Engineering LLC
1 Cameron St
Wellesley, MA 02482
USA

www.AUSTINPOWERENG.com
yang.yong@austinpowereng.com

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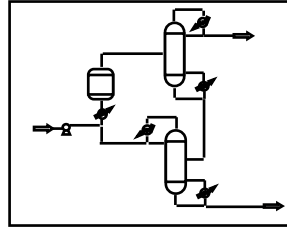
Combining performance and cost models will easily generate cost results, even when varying the design inputs.

Conceptual Design



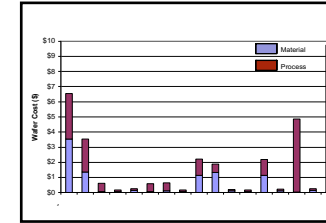
- ◆ System layout and equipment requirements

Process Simulation



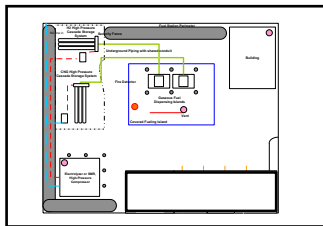
- ◆ Energy requirements
- ◆ Equipment size/ specs

Process Cost Calcs



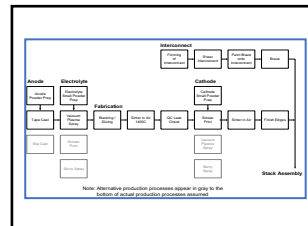
- ◆ Process cost
- ◆ Material cost

Site Plans



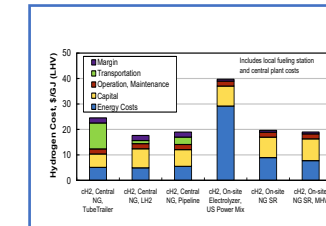
- ◆ Safety equipment, site prep, land costs

Capital Cost Estimates



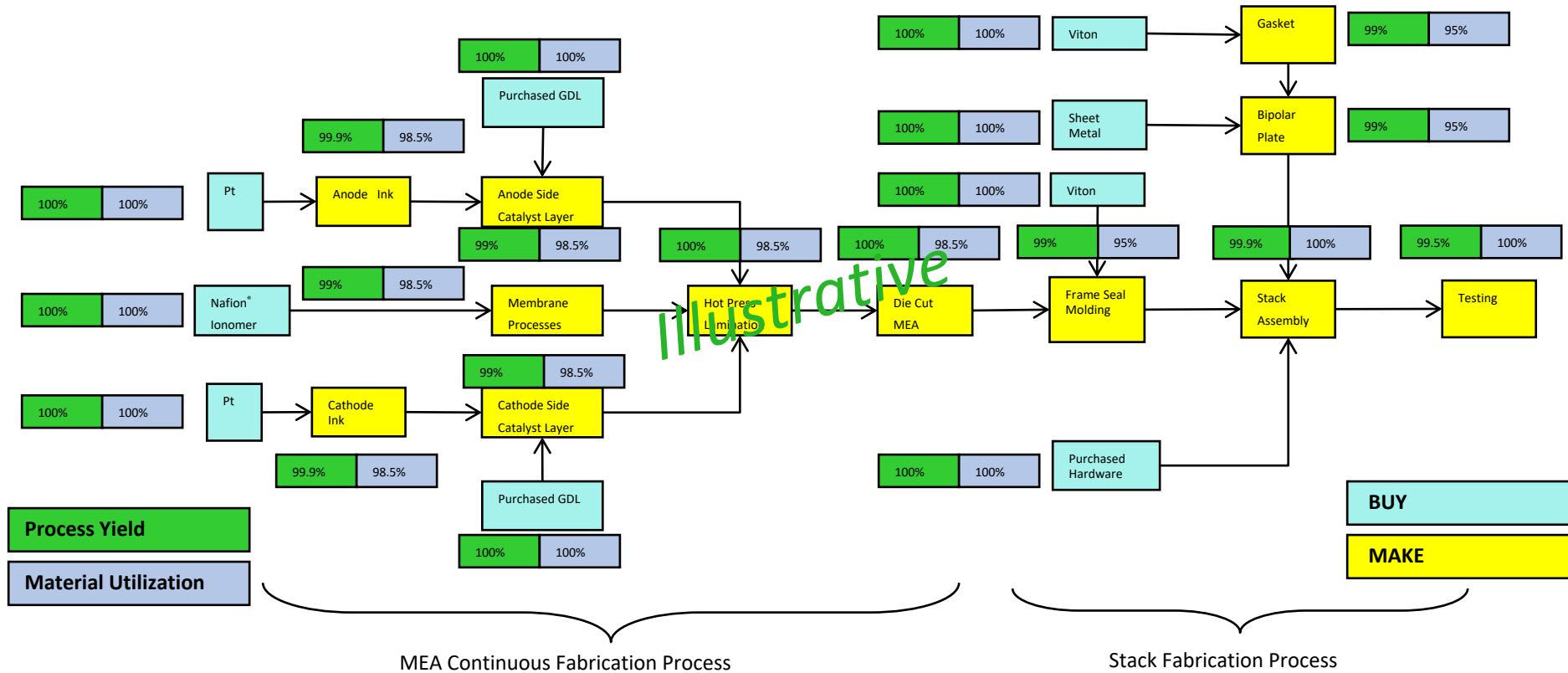
- ◆ High and low volume equipment costs

Product Costs



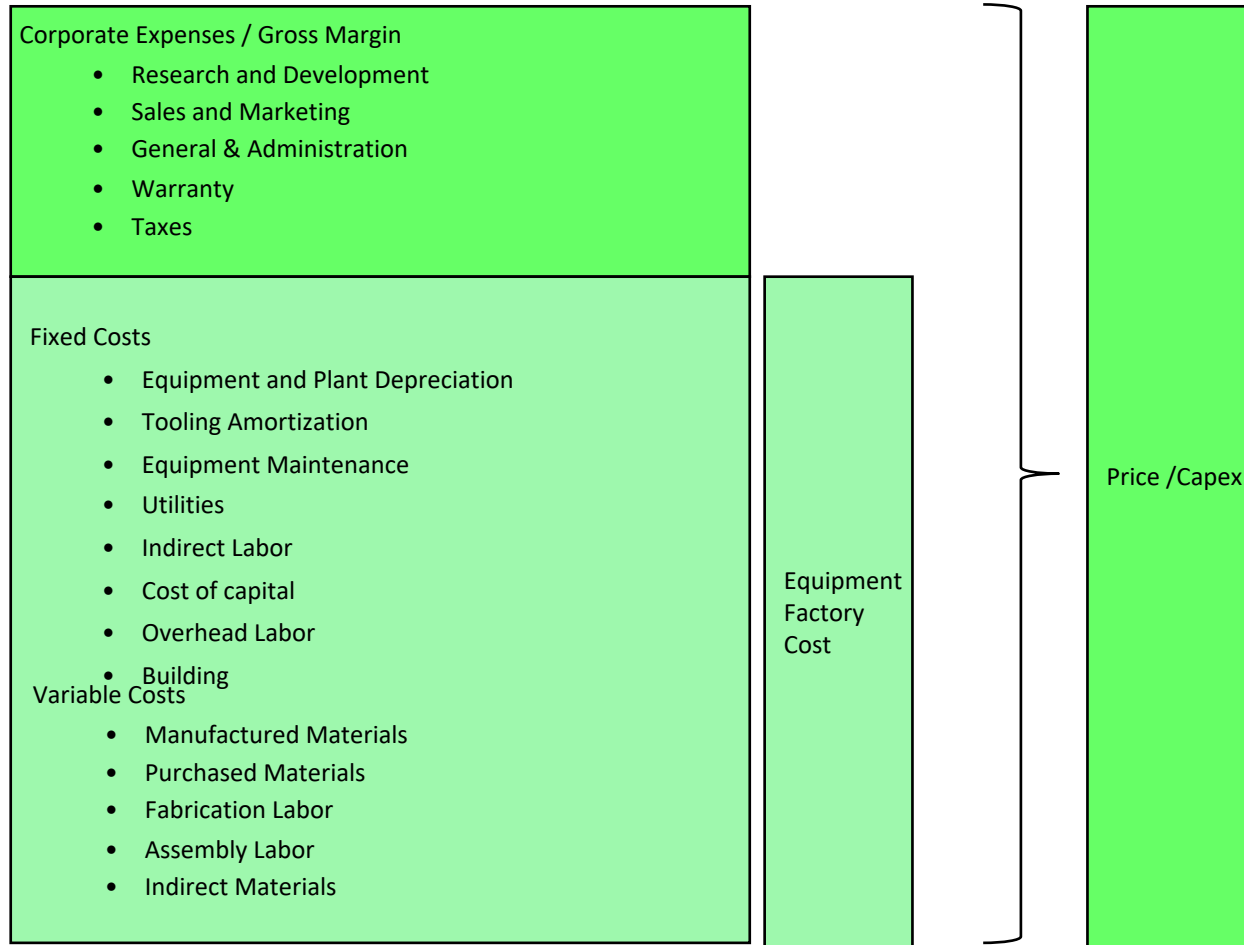
- ◆ Product cost (capital, O&M, etc.)

The bottom-up cost approach will be used to capture the manufacturing costs for each fabrication step accurately.



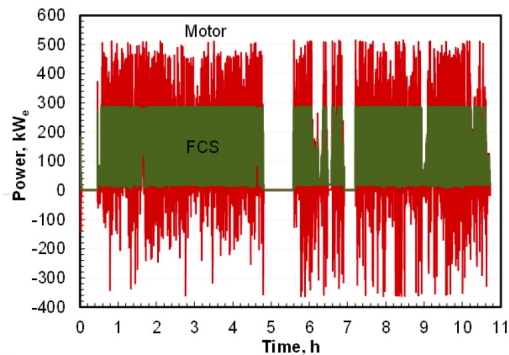
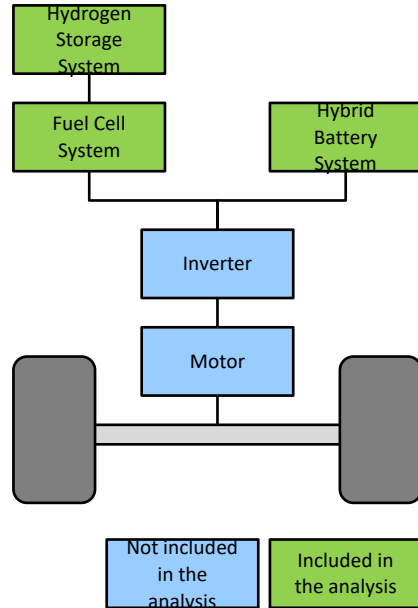
True-value-mapping analysis virtualizes costs in each fabrication step, breaking costs down into materials, labor, capex, utility, maintenance, etc.

Cost structures / categories used in our analysis:



Project Scope

Conduct a bottom-up manufacturing cost analysis of a 275 kW_{net} class 8 truck fuel cell power system.



* Data from M2FCT: Million Mile Fuel Cell Truck Consortium, DOE AMR, 2022, Adam Webber

275 kW_{net} Class 8 Long Haul Fuel Cell Truck

Fuel cell power: 275 kW_{net} (EOL)

Battery power: 225 kW

Battery energy: 70 kWh

Motor power: ~500 kW

H2 storage: 60 kg (Six tanks)

H2 storage tank: Cryo-compressed

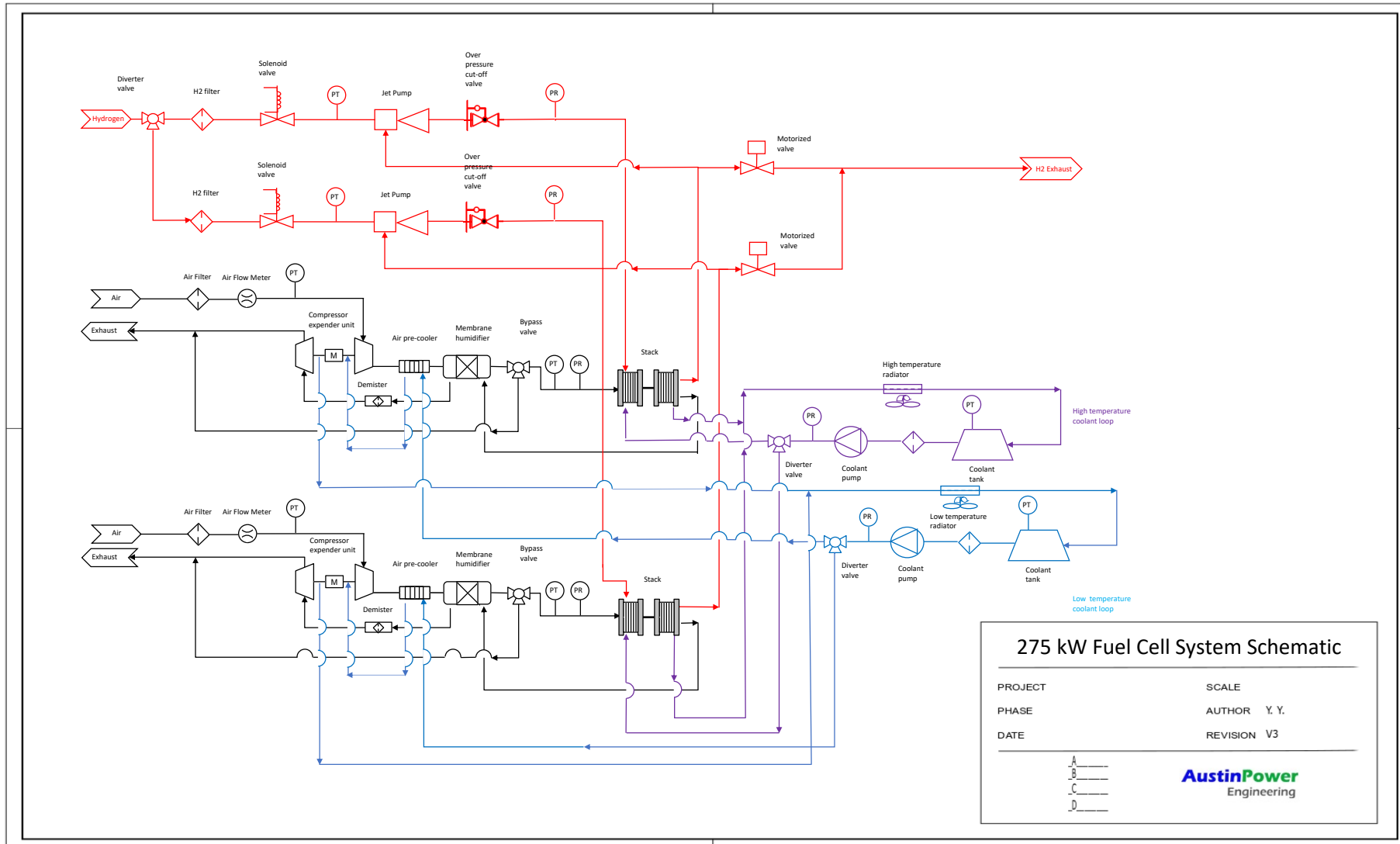
System Components	Class 8 Truck
Vehicle production volume (unit/year)	1,000, 10,000, 100,000
Stack source	Assume 275kW _{net} stacks at the annual production volume of 1,000, 10,000, 100,000 units
H2 storage system production volume	10 kg x 6 cryo-compressed H2 tanks at an annual production volume of 1,000, 10,000, 100,000 units
Battery source	70 kWh lithium-ion battery pack

System and material assumptions for the cost estimation:

Stack Components	Unit	Current System	Comments
Production volume	systems/year	1,000, 10,000, 100,000	Baseline 10,000
System net power (EOL)	kW	275	DOE M2FCT
System gross power (EOL)	kW	335	
# of stacks in the system	#	4	
Stack' net power	kW	69	
Stacks' gross power	kW	84	
Cell power density (EOL)	mW/cm ²	600	DOE M2FCT
Cell Voltage (EOL)	Volt	0.7	DOE M2FCT
Platinum price	\$/tr.oz.	\$1,000	Feb, 2023
Pt loading (EOL)*	mg/cm ²	0.45	DOE M2FCT
Membrane type		Reinforced PFSA	
Membrane thickness	micro meter	14	
GDL layer		Non-woven carbon paper with MPL layer	
GDL thickness	micro meter	110	@50 kPa pressure
MPL layer thickness	micro meter	45	
MEA gasket material		PET	
MEA gasket thickness	micro meter	100	
Bipolar plate type		TiOx coated SS316	Treadstone; Near term
Bipolar plate base material Thickness	micro meter	100	
Seal material		EPDM	

- Data from M2FCT: Million Mile Fuel Cell Truck Consortium, DOE AMR, 2022, Adam Webber
 - The required membrane area and allowance for degradation to reach 25,000h electrode lifetime are smaller for higher Pt loading in the cathode electrode
 - - 0.25 mg/cm² Pt loading: 73 m² membrane area, 120% allowance for catalyst degradation
 - - 0.40 mg/cm² Pt loading: 59.4 m² membrane area, ~100% allowance for catalyst degradation (used in this analysis)
 - Estimated 69% electrochemical surface area (ECSA) loss after 25,000 hours at EOL on Class 8 Drive Cycle from degradation Model: 56.5%

The 275 kW direct hydrogen PEM fuel cell system configuration:



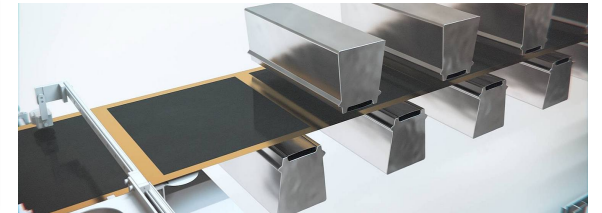
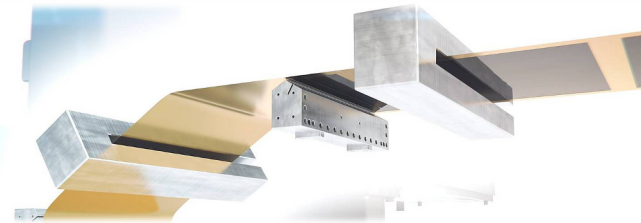
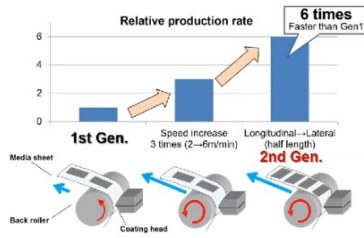
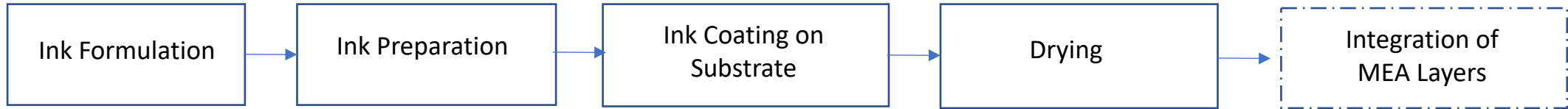
275 kW Fuel Cell System Schematic

PROJECT	SCALE
PHASE	AUTHOR Y. Y.
DATE	REVISION V3

A _____
 B _____
 C _____
 D _____

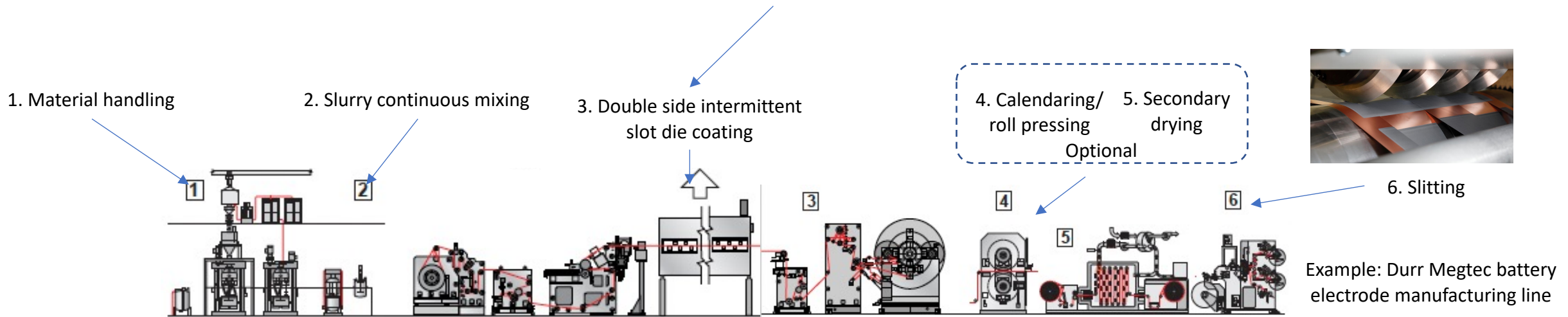
AustinPower
Engineering

We developed a double-sided intermittent slot die coating process for future mass production coating process based on current lithium-ion battery coating processes.

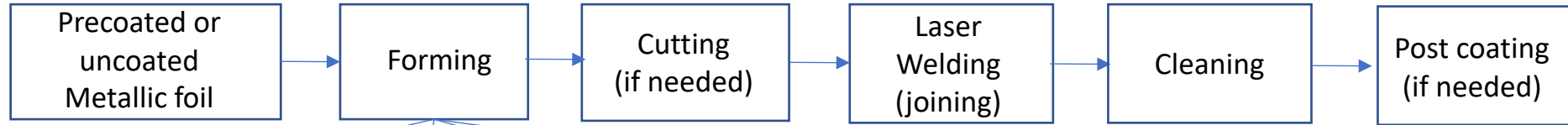


Example: Current Toyota fuel cell electrode coating

Example: Durr Megtec double size coating & contactless air drying for battery manufacturing



The high-velocity forming is an overall better solution.



Conventional progressive die stamping

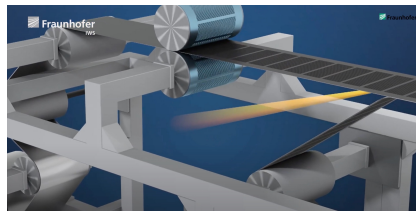
- Tooling cost high
- Need lubrication
- Cutting module life short
- Not friendly with precoated materials

R2R roller forming

- Early development



*Manufacturing of Metallic Bipolar Plate Channels by Rolling, Alexander Bauer, J. Manuf. Mater. Process. 2019, 3, 48; doi:10.3390/jmmp3020048



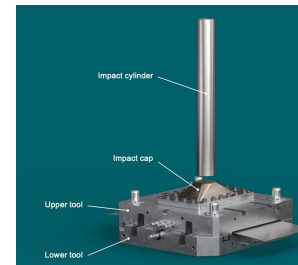
Fraunhofer IWS concept design

Hydroforming

- Larger press force required
- Need lubricants

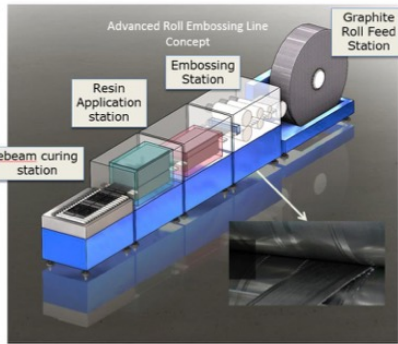
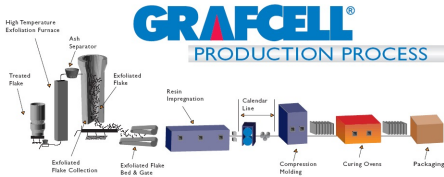
High velocity forming

- Low capex & opex
- No lubricants
- Low power consumption



From: Cell Impact

R2R graphite foil production has been demonstrated by a few developers.



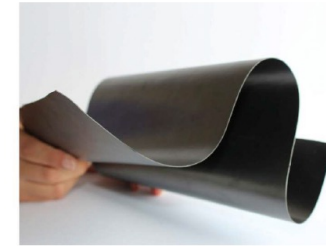
Neograf/Graftech
USA



Demonstration for 9 meters/min process



Matthews Saueressig
Engineering Group(acquired
Terrella Energy Systems Ltd.),
USA and Illuming Power
(Canada)



Highly flexible bipolar plate. Credit: Fraunhofer
UMSICHT

KONTIFLEX: Mass production of graphite bipolar plates

Continuous production of flexible bipolar plates for PEM fuel cells using the roll-to-roll process

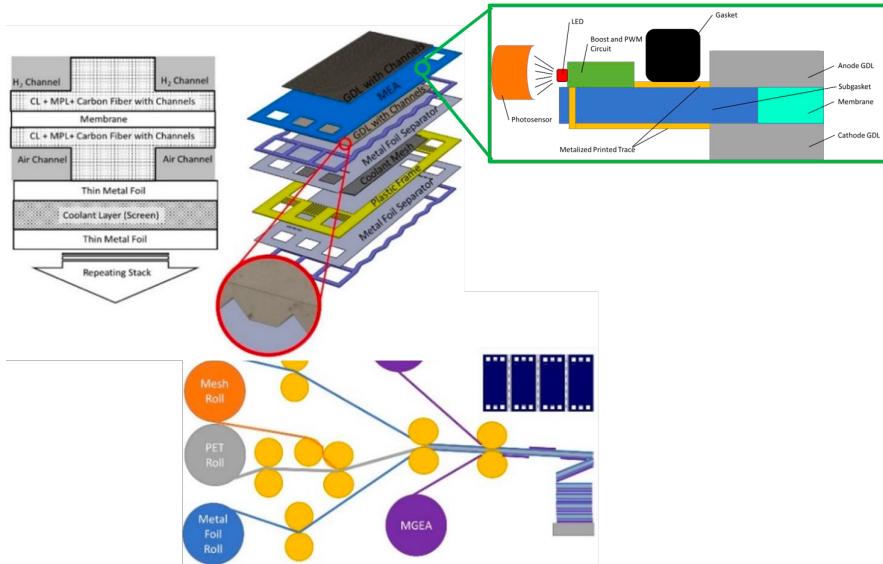
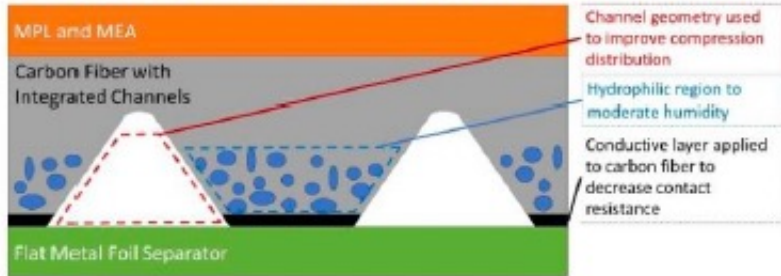
World's largest bipolar plate

Contact
Dr. Ingo Armin Groll
Head of Cooperative Electrochemical Energy Storage Group, Research Center for Chemical Energy Storage
Phone: +49 208 8008-1211
www.kontiflex.com
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Fraunhofer
Germany

R2R based stack assembly is under development.

Improved GDL compression stiffness, multi-phase transport, and MEA/coolant dT



From: Plug DOE AMR 2022

J. Chen et al. / Journal of Manufacturing Processes 23 (2016) 175–182

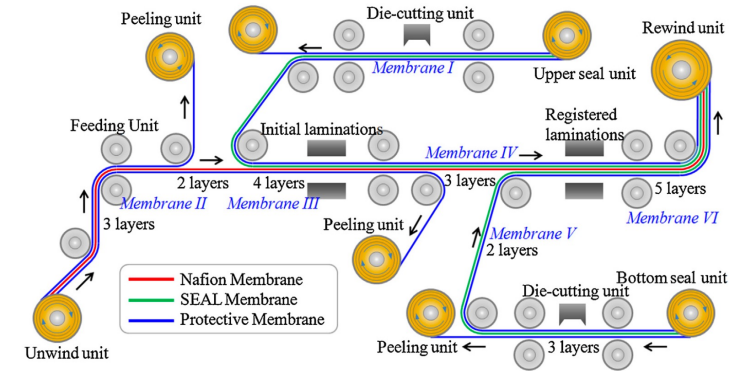


Fig. 3. A detailed flow diagram of MEA lamination process.

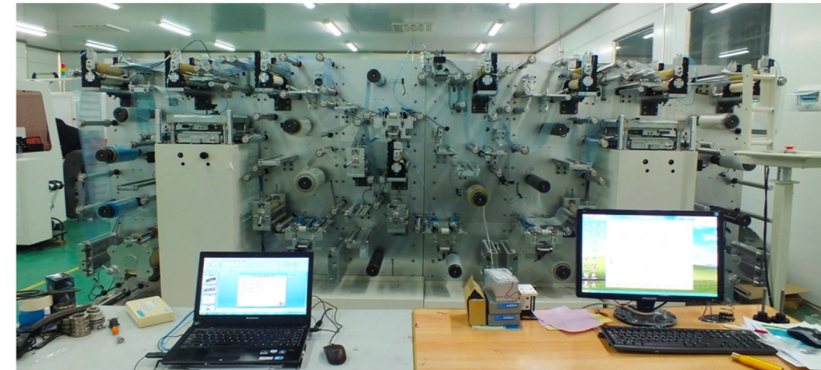
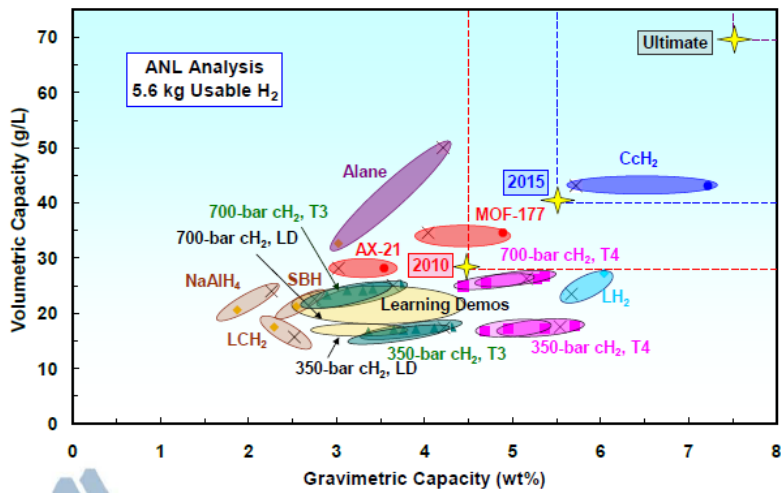


Fig. 4. Layout of seal lamination equipment. (a) Schematic diagram of layout of seal lamination equipment and (b) picture of real seal lamination equipment.

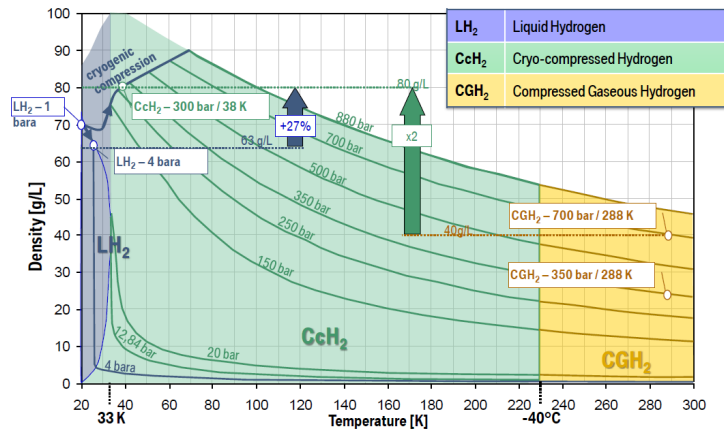
- Demonstrated membrane and frame seals R2R lamination
- Further MEA and GDLs R2R lamination to be demonstrated

High-rate roll-to-roll stack and lamination of multilayer structured membrane electrode assembly, J. Chen et al. / Journal of Manufacturing Processes 23 (2016) 175–182

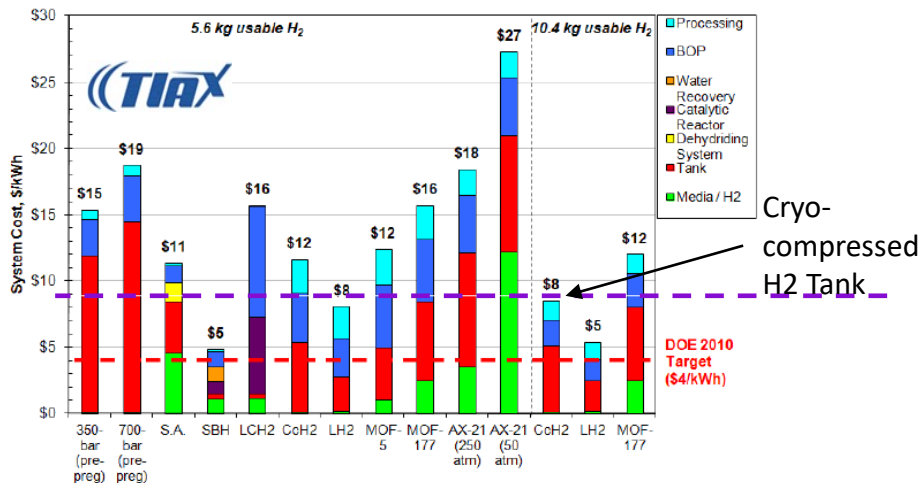
The cryo-compressed CH_2 hydrogen tank has advantages in gravimetric density, volumetric density, and cost.



BMW HYDROGEN STORAGE. CcH_2 – CRYOGENIC GAS DENSER THAN LH_2 .

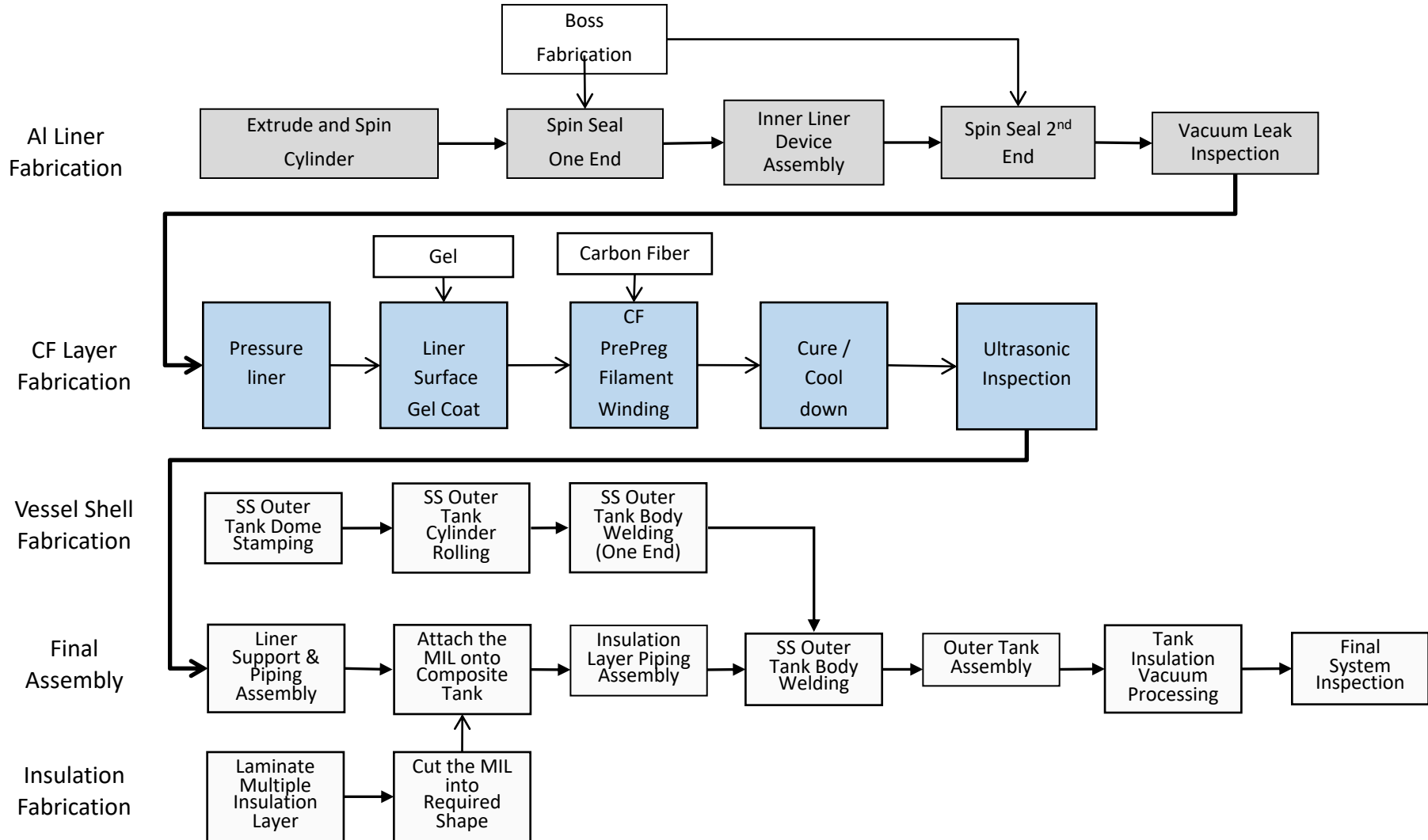


- US Department of Energy Hydrogen Storage Cost Analysis, 2013, TIAX; Cost is based on 500,000 units/year
- System level analysis of hydrogen storage options, R. K. Ahluwalia, 2010
- Cryo-compressed hydrogen storage, BMW 2012



Stack Components	Unit	Class 8 Truck
Production volume	tanks/year	60,000
Usable hydrogen	Kg	10.1
Total H2 in the tank	Kg	10.7
Tank type		III
Tank max pressure	PSI	5,000
# of tanks	Per System	6
Safety factor		2.25
Tank length/diameter ratio		3:1
Liner material		Al
Liner thickness	mm	3
Carbon fiber type		Toray T700S
Carbon fiber cost	\$/lbs	12
Carbon fiber vs. resin ratio		0.68:0.32
Carbon fiber translational Strength factor		81.5%
Carbon fiber composite layer thickness	mm	12
Vacuum gap	mm	40
# of MLVI layer		40
Outer layer		SS304
Outer layer thickness	mm	3

A vertically integrated manufacturing process is assumed for the tank and BOP components.



Fuel cell system and hydrogen storage cost analyses are typically done separately and use different measures, but we wanted to compare them jointly to batteries.

Fuel cell system costs are measured in \$/kW

Current Class 8 truck fuel cell systems cost \$200~\$450/kW by production volumes

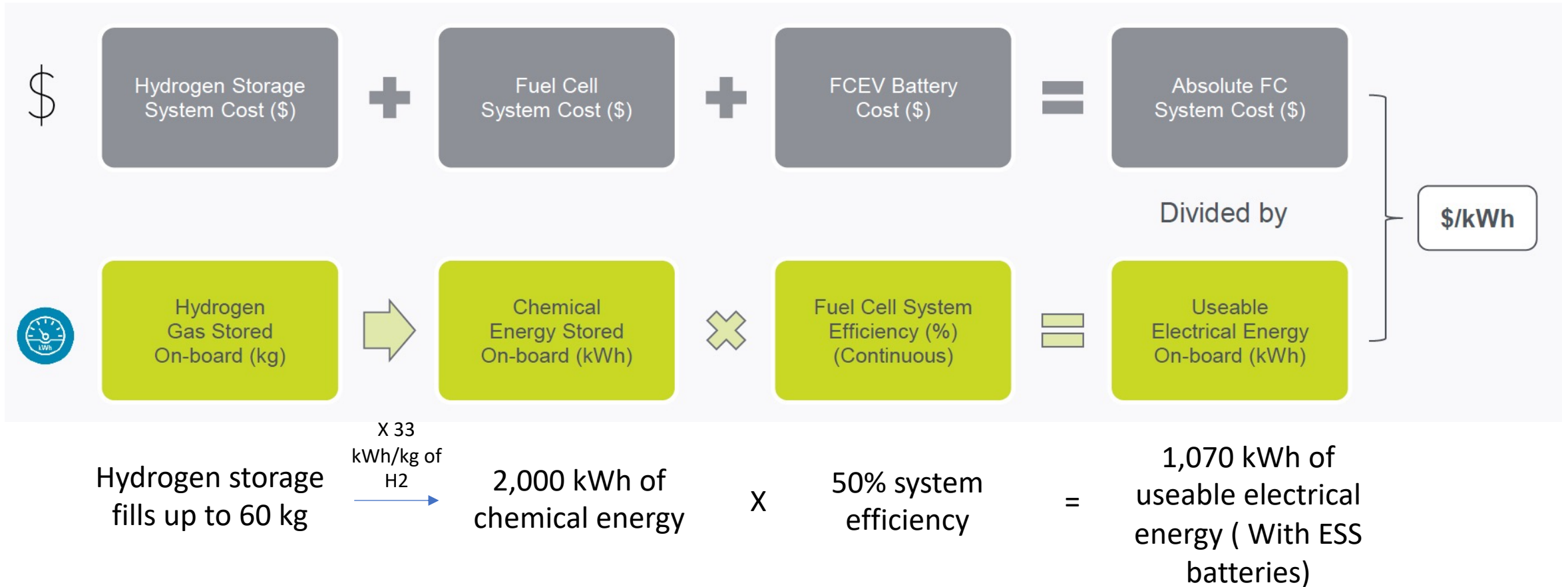
Hydrogen storage system costs are measured in \$/kWh like batteries.

Current on-board hydrogen storage systems cost \$15~25/kWh by production volumes

How can we combine the costs so we can compare them jointly to batteries?

Jointly Comparing Fuel Cell System and Hydrogen Storage Costs

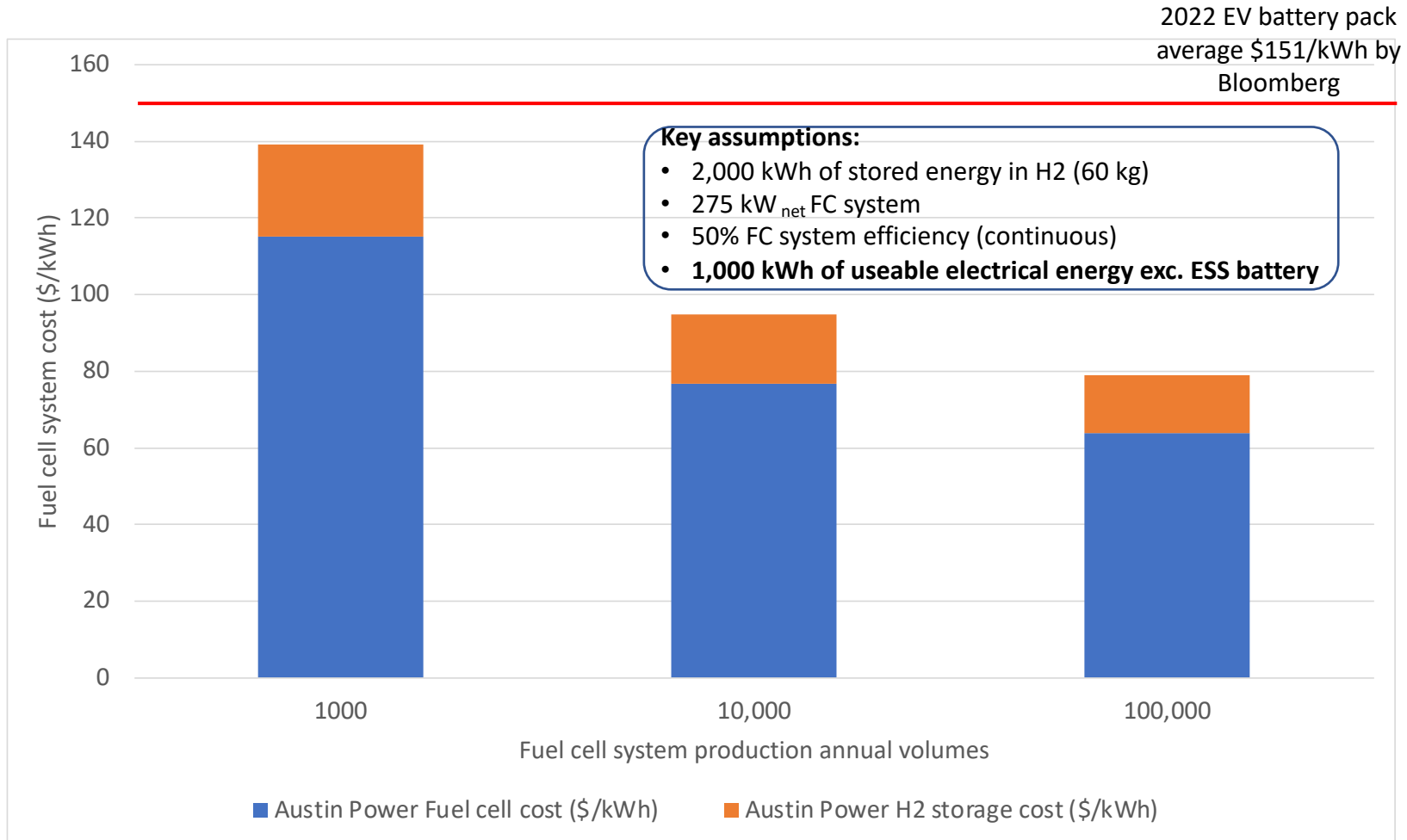
Method to get the fuel cell and hydrogen tank system costs in \$/kWh.



Collaboration with Advanced Propulsion Centre UK, Luke Bates, 2022

Jointly Comparing Fuel Cell System and Hydrogen Storage Costs

If we look at the combined cost of the fuel cell system and hydrogen storage system in \$/kWh, we have a better cost advantage than batteries.



- Battery price: <https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/>

Thank You!

Contact: Yong Yang

Austin Power Engineering LLC

1 Cameron St,
Wellesley, MA 02482
USA

+1 401-829-9239

yang.yong@austinpowereng.com

www.austinpowereng.com