LT PEM Cell and Stack Manufacturing Automation: Techno-economic Analysis

2022 DOE Manufacturing Automation and Recycling for Clean Hydrogen Technologies Experts Meeting

Brian D. James
Jennie Huya-Kuadio
Kevin McNamara
Strategic Analysis Inc.

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Objective

- Provide guidance to DOE/Workshop attendees on:
  - where new & improved automation approaches might best impact cost & throughput
  - remaining RD&D gaps
- Relate ongoing SA Technoeconomic (DFMA) cost analysis to automation
- Focus on automation for low-temperature fuel cells and electrolyzers

Overview

Automation is a broad topic. Today's presentation will focus on select elements of PEM FC & Electrolyzer Fabrication/Assembly

Application

- Fuel Cells
- Electrolyzers

Technology

- Low Temperature (PEM, ALK)
- High Temperature (Solid Oxide)

Automation Opportunity

Cell Formation
- BPP stamping, molding, embossing
- BPA Joining (welding, adhesive)

Leak Test
- BPP leak test
- BPA leak test
- MEA leak test
- Module leak test
- Stack leak test

MEA Fab/Assy
- Membrane casting/formation
- Catalyst application
- MEA assembly
- Gasket joining/applic.

Cell Stacking
- Stacking
- Compression
- Banding/tie-rods
- Integrated leak test

Stack Testing/ Conditioning
- Module/Stack leak test
- End-of-Line (EOL) functionality test
- Conditioning

Other
- GDL
- Endplates
- Others

Common Trends

- Desire for automation driven by:
  - Primary: lower cost, higher yield (increased accuracy, fewer errors)
  - Secondary: less floorspace, less labor uncertainty, reduced # of parallel lines
- Automation best serves repeat units of stacks
  - Although also may benefit non-repeat components (endplates, BOP, etc.)
- Two main thrusts (but there are others!)
  - Pick & Place Robots vs. Roll-to-Roll (R2R) equipment
- Minimize parts handling (by delaying singulation as long as possible)
- Many (all?) traditional operations require some form of high-speed loading/unloading
  - leak test, screen printing, ovens, PVD, etc.

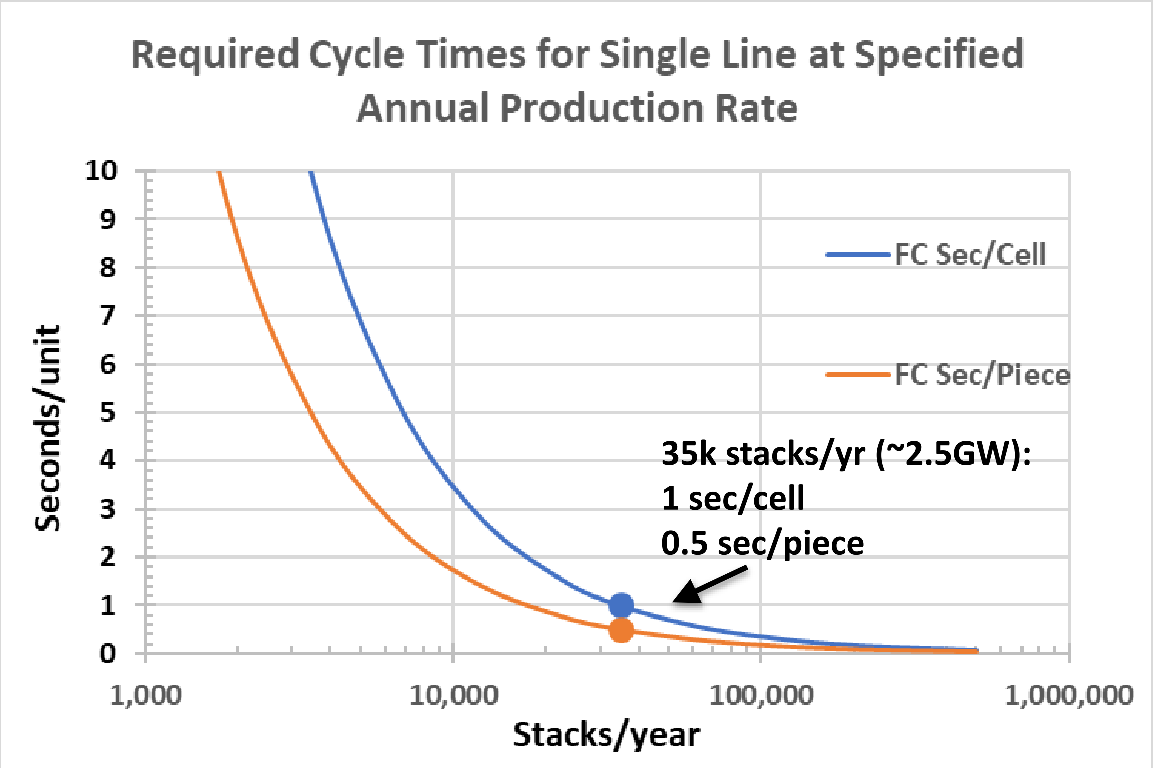
Notional PEM Stacks

- 80 kW_{net} Light Duty Vehicle
  - 1 stack per system
  - 310 cells per stack
  - 250-400cm² active area
  - 400-600 cm² total area
  - Max: 500k systems/year
    - 500k stacks
    - 155M cells (BPA)
    - 310M plates (BPP)
    - 40 GW/year (net)
- 275 kW_{net} Heavy Duty Vehicle
  - 4 stack per system
  - 400 cells per stack
  - 400-800 cm² active area
  - 600-1,300 cm² total area
  - Max: 100k systems/year
    - 400k stacks
    - 160M cells (BPA)
    - 320M plates (BPP)
    - 27.5 GW/year (net)
- 1 MW PEM Electrolyzer
  - 100 stacks per 100 MW system
  - 150 cells per stack
  - ~1,800 cm² active area
  - ~3,000 cm² total area
  - Max: 50 systems/year (5 GW)
    - 5k stacks
    - 750k cells
    - 750k plates/GDL/PTL/CCM
    - 5 GW/year

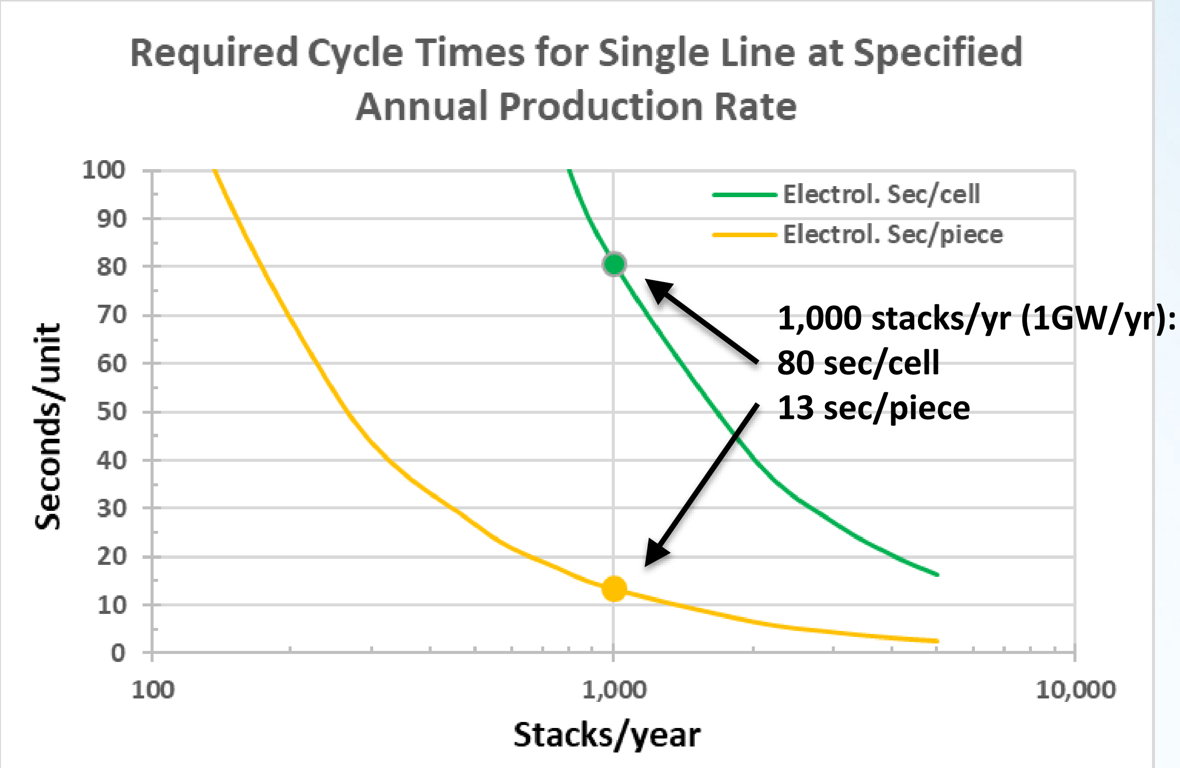
Fast Handling/Processing Cycle Times are Required for High Volume Operation

Fuel cells are the driving application due to higher expected cell count (smaller cell size, higher stack demand).

Fuel Cells



Electrolyzers



Based on:
2 shifts/day
7 productive hours/shift
240 work-days/year
FC: 350 cells/stack, 2 pieces/cell, 80kW stack
Electrol.: 150 cells/stack, 6 pieces/cell, 1MW stack

- A single FC line with ~35k stacks/year, requires a ~1 sec/cell effective cycle time
- A single Electrolyzer line with ~1k stacks/year (~1GW/yr), requires an 80 sec/cell effect. cycle time

Equipment Flexibility Desired by Stack OEMs

(General desire for equipment to handle multiple products)

Cell Stacking

- Possible to use the same cell stacking process line for FC and electrolyzer stacks
  - Within reasonable part size limits (PEM FC/electrolyzers fine, Alkaline more questionable)
- Number of individual component parts different:
  - Fuel Cell: 2-3 parts per cell
  - Electrolyzer: 5+ parts per cell

MEA Assembly

- R2R Assembly/Fabrication
  - Some flexibility to change cell sizes but a considerable effort. Impacts include:
    1. Impact to line speed change hardware and software
    2. Change of Tooling/Dies
    3. Re-calibration of process line (including web guiding, tension control, and camera systems)
    4. Set-up time (6-8 days) for 2nd design
    5. Down time for replacements/adjustments/recalibration: >5 hours (once set up for two process)
    6. In total, could be >$400k and >1 week to reconfigure R2R line
- Pick-and-Place Assembly
  - Generally better flexibility to handle part size and part number variations
  - Trade-offs in cycle time and system cost

Level of Automation Demonstrated for Each Stack Component

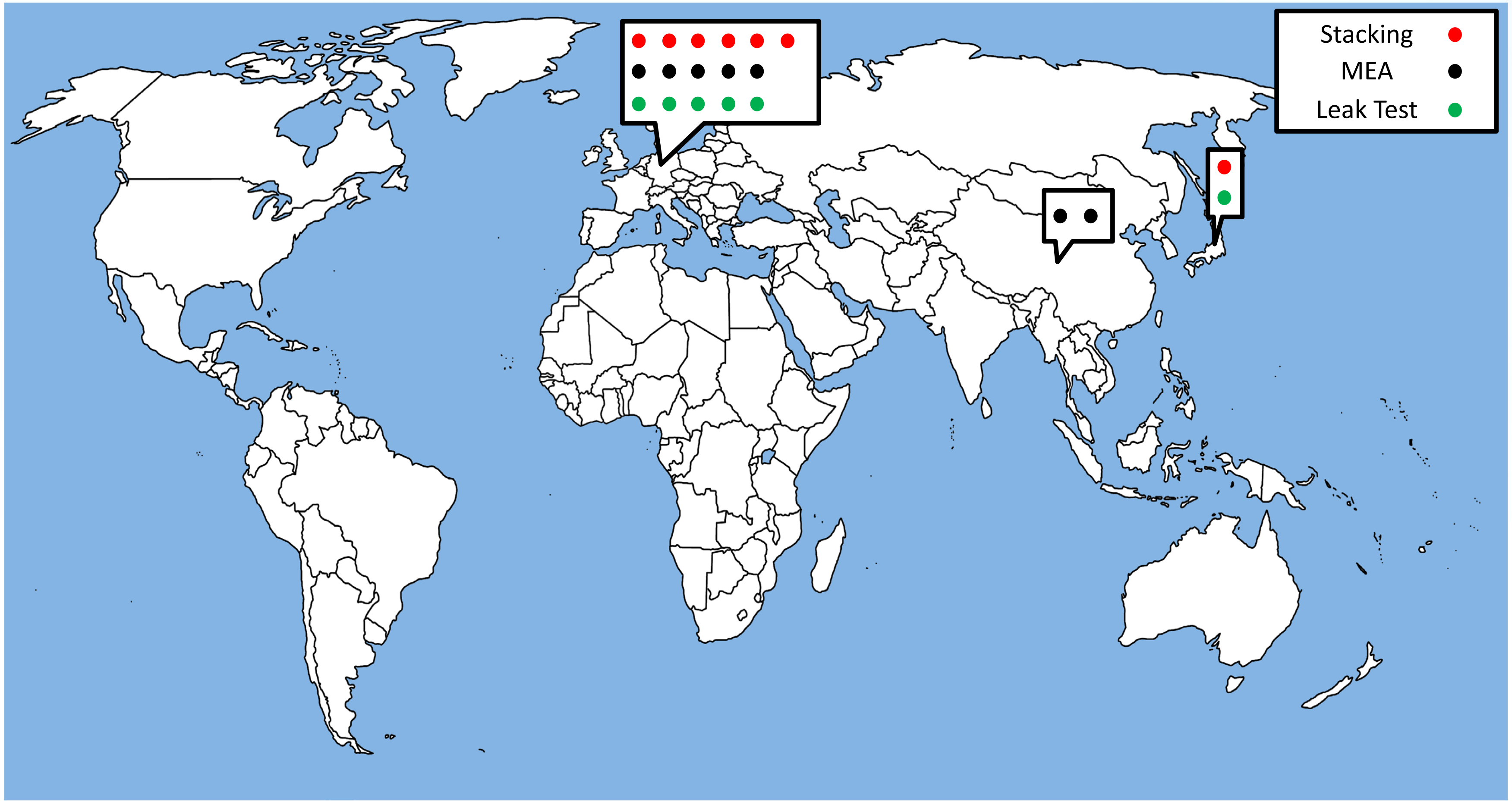
- Numerous recent discussions with automation suppliers show a broad range in capital cost and cycle times, however, all have common goals
- Faster machines require fewer parallel lines
- Cell Stacking, banding, leak testing can all be conducted in-line

Component	Current Capabilities	Next-Gen Target (Prelim.)	Other Notes
Membrane	R2R: TBD cycle time	R2R: TBD cycle time	Manufacturing process unlikely to change in future
Catalyst Coated Membrane (CCM)	R2R: 10m/min, ~1.5 sec/CCM	R2R: >=15m/min, ~0.5 sec/CCM	Manufacturing process unlikely to change in future
Gas Diffusion Layer (GDL)	R2R: TBD cycle time	R2R: <0.5 sec/GDL	Manufacturing process unlikely to change in future
Bipolar Plate (BPP)	Metallic: 0.8- 3.5 sec/BPP Graphite: TBD sec/BPP	Metallic: <0.5 sec/BPP Graphite: <0.5 sec/BPP	**Considerable effort needed to achieve high volumes without many simultaneous production lines**
Membrane Electrode Assembly (MEA) (Assembly of the MEA)	Pick-&-Place: >15 sec/MEA (manual)	Roll-to-Piece: <1 sec/MEA Input: rolls of CCM, Gasket, GDL Output: discretized UMEA	R2R MEA fabrication has been demonstrated on pilot lines and likely the next step for high volume MEAs
Cell Stacking	Pick-&-Place: 3-6 s/cell typical, 1 s/cell prototype demo	Pick-&-Place: 0.5-1 sec/cell	Manufacturing process likely to change in future to achieve << 1 sec/cell
Seals (on BPP or MEA)	Screen print: 2-3 sec/BPP	Screen print/Other: <1 sec/BPP	Manufacturing process likely to change in future to achieve < 1 sec/BPP

- (FC/Electrolyzer automation equipment) Industry experiencing rapid product development.
- Next step in production seems to be process lines capable of 20k to 40k stacks per year, then jump to >100k stacks/yr

Recent investigation of Stacking, MEA Assy, and Leak Test equipment vendors shows considerable recent activity*

Companies are global providers, some with US subsidiaries.



* Meant to be illustrative of trends, not a comprehensive company listing

Bipolar-Plate/Separator Manufacturing Needs

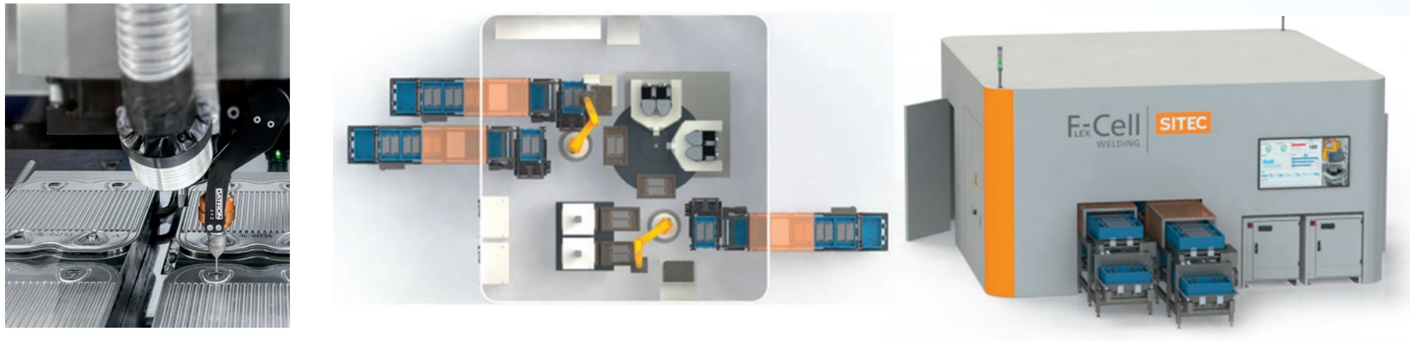
- **Metallic Plates**
  - **<u>Forming via Stamping</u>: current processes will require many simultaneous production lines to meet high-volume capacity**
  - <u>Coating via PVD or other</u>: pre-coat coil before stamping reduces additional handling of thin parts
  - **<u>Laser Welding (FCs)</u>: limits to laser speed due to thickness of plates and potential spatter. Need for engineering solutions to reduce simultaneous lines**
  - <u>Gasket Seal via screen print or insertion mold</u>: Slow indexed process

Source: Schuler Group (50k stacks/yr, 1sec/plate) https://www.schulergroup.com/major/us/technologien/produkte/brennstoffzellen/index.html

Number of Simultaneous Production Lines for BPP Forming

LDV: 500k sys/yr at 300 cells/stack (single plate/stamp)

		Operational Up Time (hr/yr)				
		3360	4000	5000	6000	8760
Effective Stamping Cycle Time (sec/part)	0.33	8	7	6	5	3
	0.5	12	10	8	7	5
	1	25	21	17	14	10
	2	50	42	33	28	19
	3	83	69	56	46	32

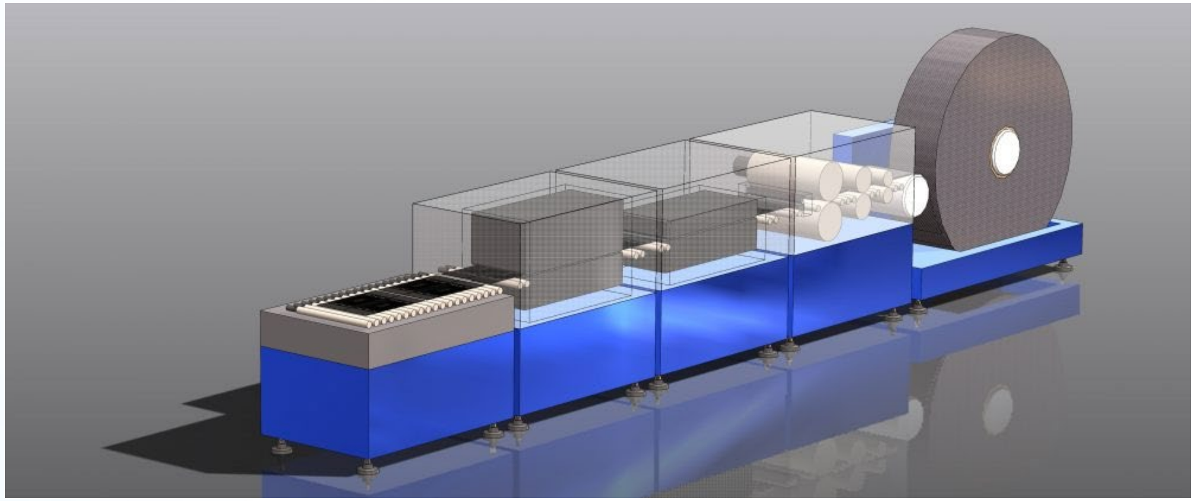


Source: SITEC (~17k stacks/yr, 3sec/part) https://www.sitec-technology.de/bipolar_plates

Bipolar-Plate/Separator Manufacturing Needs

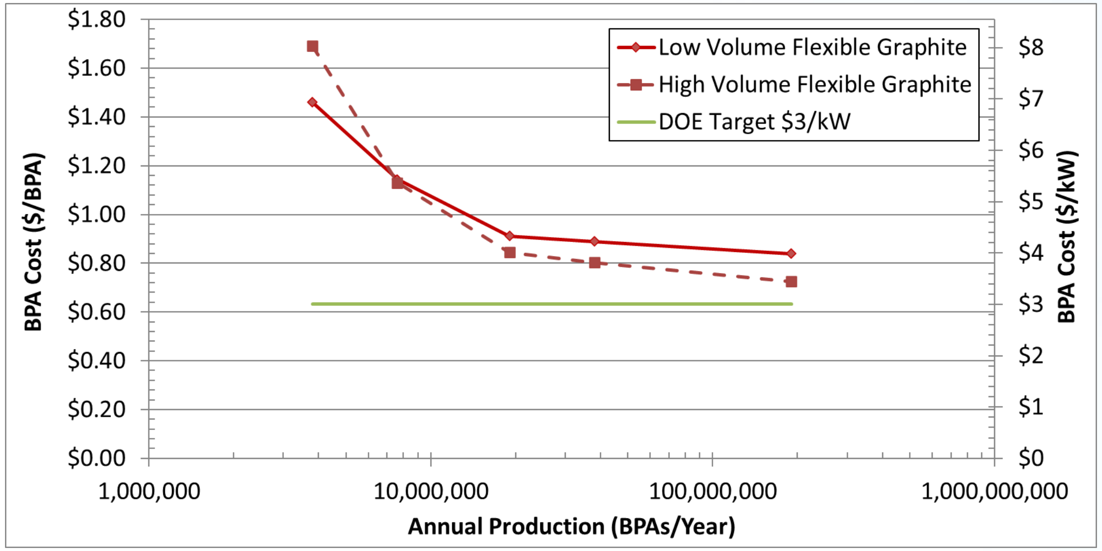
- **Composite/Graphite Plates**
  - <u>Compression Molding</u>: Common for low volume but slow cycle time
  - <u>Embossing</u>: Rotary process can be fast however in-line automated systems being developed are limited by other in-line process
  - **<u>Resin Impregnation</u>: Multi-roll batch resin impregnation systems are feasible but need R&D**
  - **<u>Resin Curing</u>: Currently hot water cured (not ideal), however, alternative methods require R&D**
  - <u>Joining two plates</u>: currently use adhesive and oven cure
  - **<u>Gasket Seal via screen print</u>: continuous screen print of interest to explore under R&D**

Embossed Flexible Graphite



Source: Terrella Energy Systems/Matthews International http://terrellaenergy.com/

SA Cost Projections for LDV



Robotic Cell Stacking

Two main Development Thrusts:

1) **Flexible Modular systems** to allow equipment customization for variety of uses/models/designs
2) **Maximize Manufacturing Speed** emphasizing high-rate production (mid/far-term use by auto OEMs)

Cell Stacking Specialization	Key Markets	Advantages	Speed Requirements	Accuracy Requirements	Typical Robotics Platform
Modular Assembly for Versatility/ Flexibility	• **Modest Production Rates Markets (but numerous models):** • Materials Handling Equipment • Marine and Rail • Stationary Power • PEM Electrolyzer	• Ability to rapidly change tooling • Cost effectively deploy multiple lines • Assemble multiple OEM products on same assembly line	• **Current Average:** 5-10s / piece • **Industry Leading:** 2-3s / piece No further speed improvements necessary (to achieve target production rates)	0.1 - 0.2 mm	Anthropomorphic (but also Cartesian, Delta, SCARA)
High Manufacturing Speed	• **High Production Rate Markets:** • Light Duty Vehicle • Heavy Duty Vehicle	• Industry leading manufacturing speed	• **Current Best:** ~1s / piece • **Future:** 0.1s / piece	0.1 mm	Cartesian, Delta, SCARA

RD&D Issues/Desires:

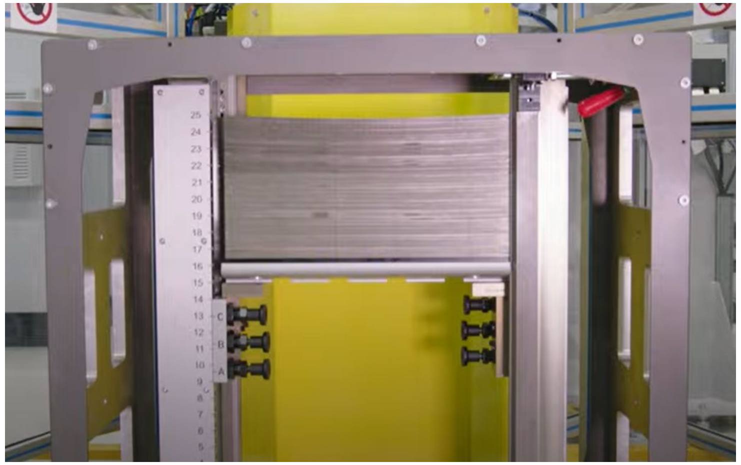
- Faster speed
- Lower capital cost
- Flexibility to handle different part sizes
- Modularity to allow cell design changes (different # of parts, etc.)
- Lightweight grippers to handle delicate, floppy parts (CCM, gaskets)
- Ability to handle release sheets
- In-line QC (optical or other) with automatic part-rejection
- Digitalization/marking/parts-tracking
- Integration with other steps (leak testing, banding)

Examples of Cell Stacking

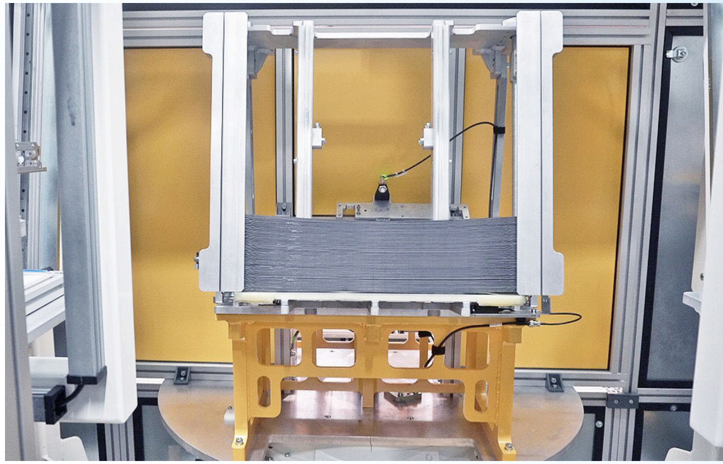
Source: **Ruhlamat**
https://www.youtube.com/watch?v=HB9AQ-2iUh4

Shows anthro. Robot P&P

Source: **BMW**
https://www.youtube.com/watch?v=NaDHSKgY_ZU

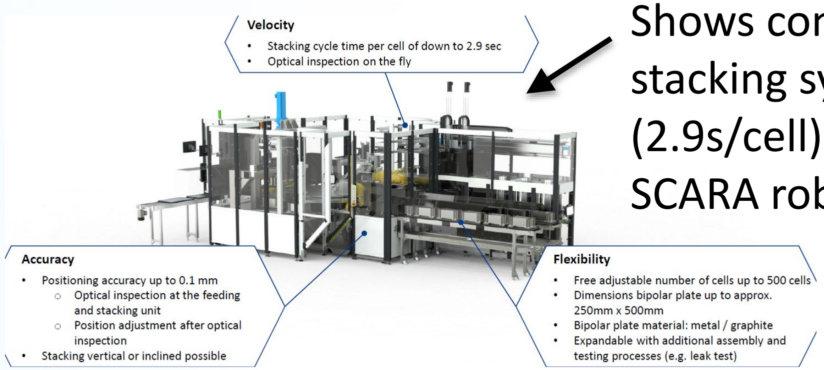


Source: **Thyssenkrupp**
https://www.thyssenkrupp-automation-engineering.com/en/automotive-industry/electric-motor-assembly/fuel-cell



Stack can "build up" or the top surface remain flat while stack is lowered.

Source: **Zeltwanger**
https://www.hannovermesse.de/apollo/hannover_messe_2022/obs/Binary/A1170562/Zeltwanger%20E-Mobility%20%281%29.pdf

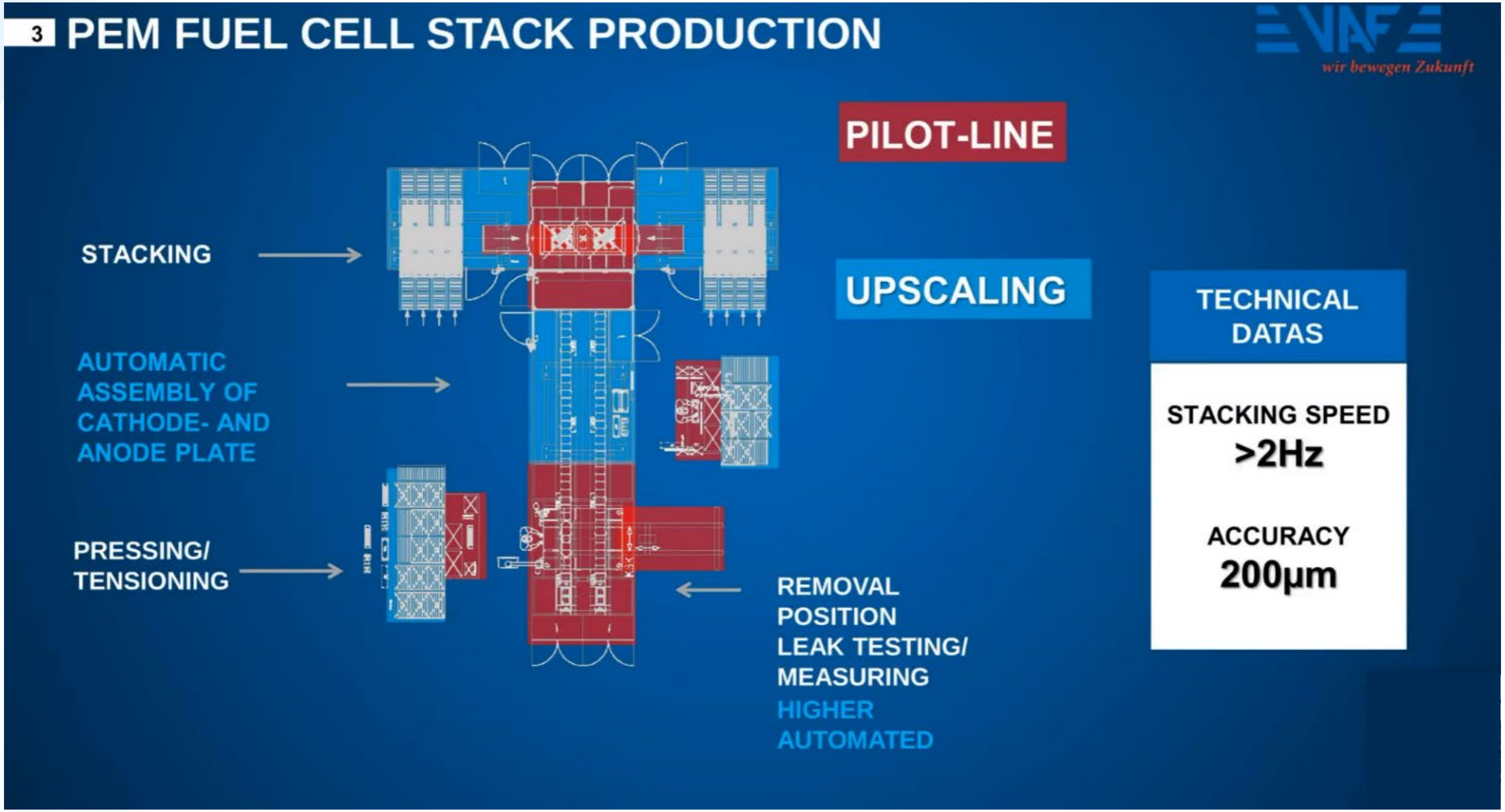


Shows complete stacking system (2.9s/cell) with SCARA robot(s)

Source: **Optima**
https://newsroom.optima-packaging.com/en/optima-packaging-group-expands-portfolio-to-include-fuel-cell-production-lines

Delta robot placing GDL

Omron/VAF Concept for Cell Stacking

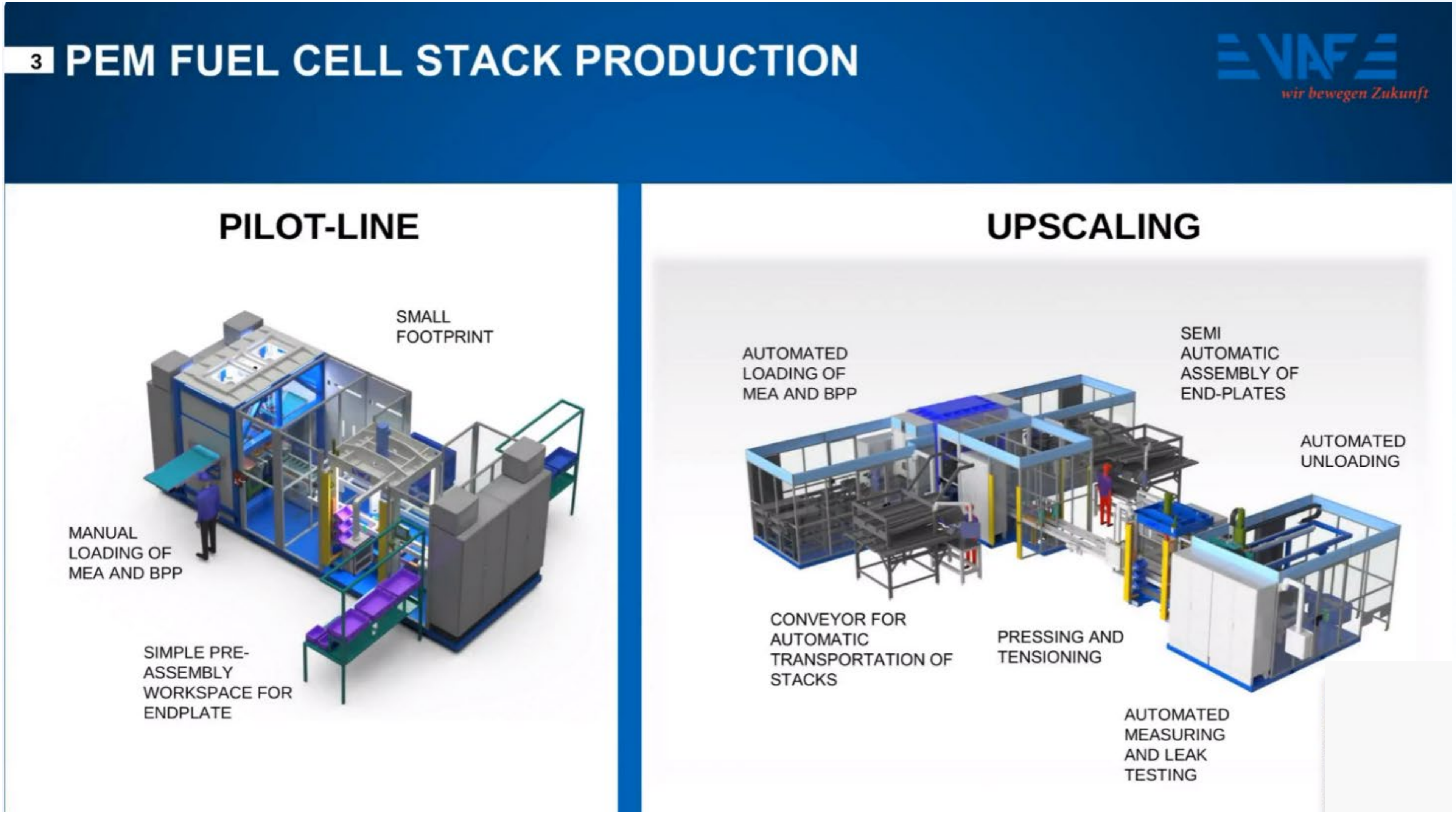


Source: Mission Hydrogen presentation by Omron and VAF. "The 8 GW Fuel cell and Electrolyzer Factory", 4 May 2022.

- Illustrates Module (or "Matrix") concept
- Integrates stack leak testing and banding

- Appears to use:
  - 2 parts/repeat cell (MEA & BPA)
  - Dual Delta robots with P&P time of ~0.4 seconds
  - Thus with 2 robots, 2 parts/cell, can to 1 repeat cell in ~1 second

Renderings of Omron/VAF Concepts

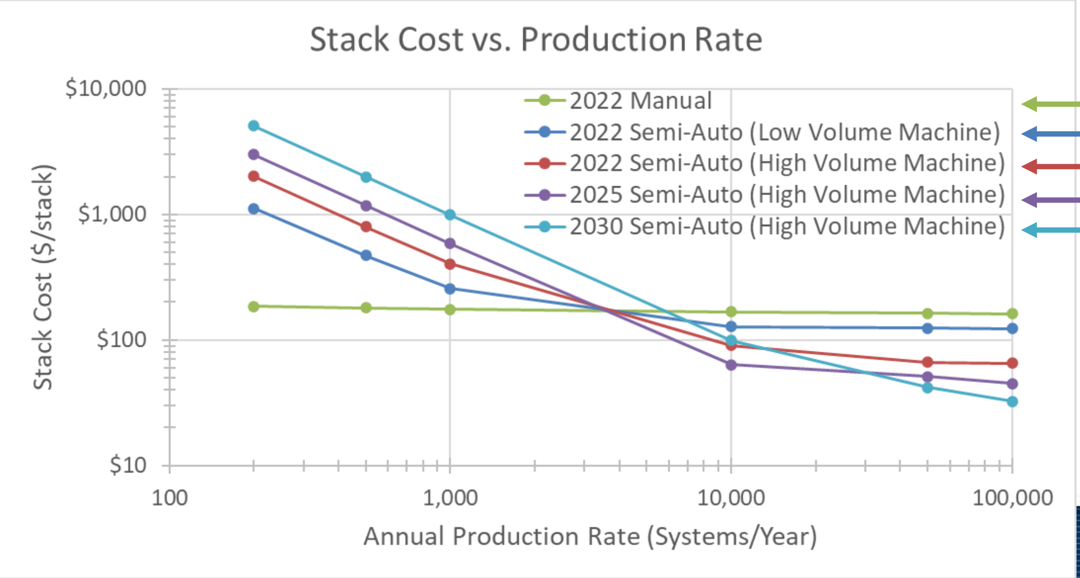


Source: Mission Hydrogen presentation by Omron and VAF. "The 8 GW Fuel cell and Electrolyzer Factory", 4 May 2022.

SA Cost Modeling of Stacking

- **Cell Stacking**
  - Robotic assembly of repeat cells (UMEA & Bipolar Plate Assembly (BPA)
  - Sub-stack or full-stack leak test
  - Assembly of endplates, current collectors, tie-rods, etc.
  - Compression and banding

Year	2022				2025			2030		
Production Rate (Systems/Year)	Manual	Low1	Med1	High1	Low2	Med2	High2	Low3	Med3	High3
P&P Time Per Part (sec/part)	10.85	3 (vendor spec.)	3 (vendor spec.)	3	3	3	0.25 (~vendor target)	3	3	0.17 (~vendor target)
Parts Per Cell	2	2	2	2	2	2	2	2	2	2
P&P Time Per Cell (sec/cell)	21.7	6	6	6	6	6	0.5	6	6	0.34
Simultaneous Robots/Workers	1	2	6	6	2	6	1	2	6	1
Effective P&P Time Per Cell (sec/cell)	21.7	3 (vendor spec.)	1 (vendor spec.)	1	3	1	0.5 (~vendor target)	3	1	0.34 (~vendor target)
Capital Cost ($/line)	$10.9K	$1.7M (~vendor ROM)	$3.1M (~vendor ROM)	$3.1M (= Med1)	$1.4M (= Low1 −15%)	$2.6M (= Med1 −15%)	$4.6M (= High1 +50%)	$1.2M (= Low2 −15%)	$2.2M (= Med2 −15%)	$3.9M (= High2 −15%)



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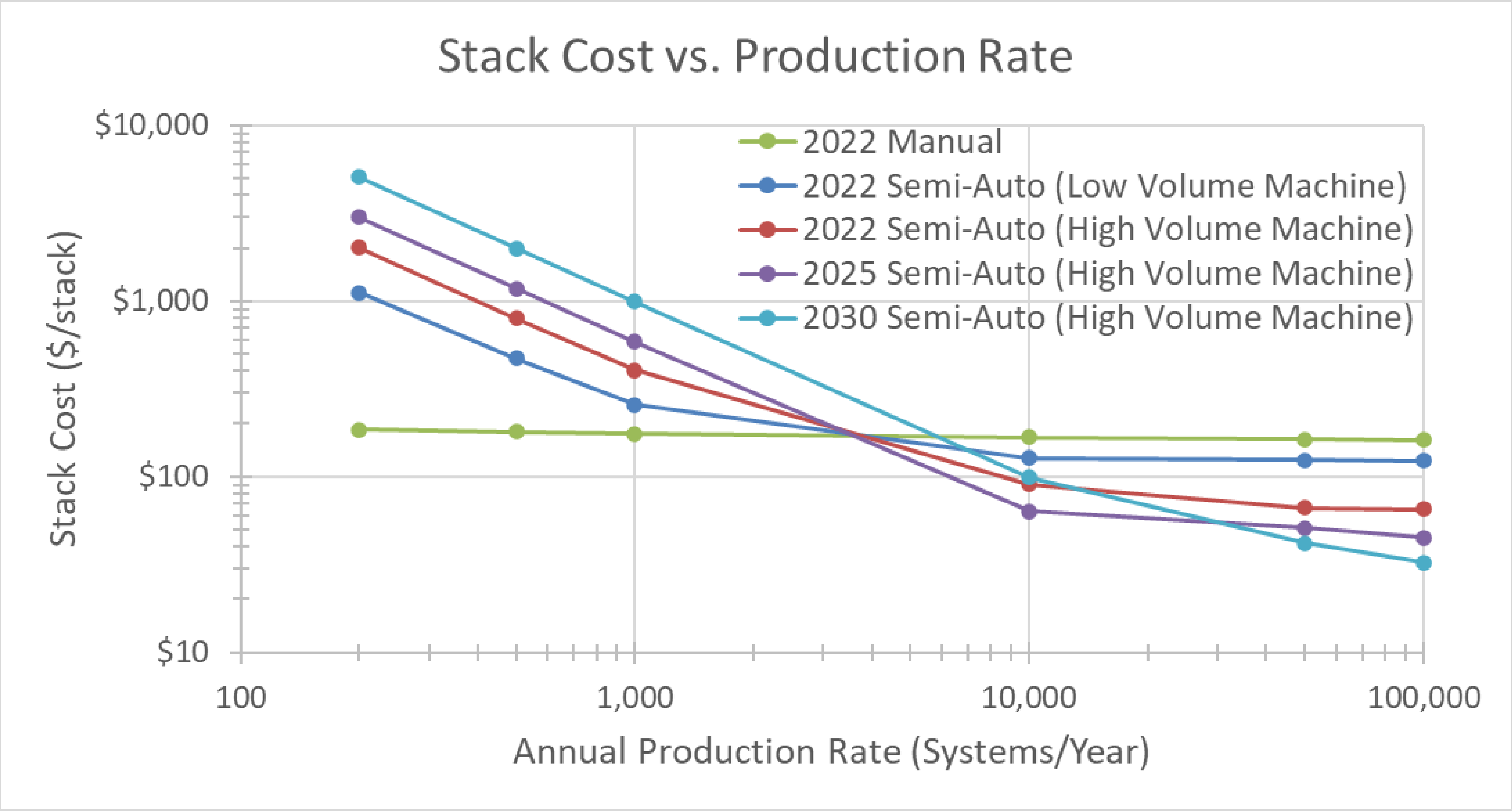
Cell Stacking Cost Comparison



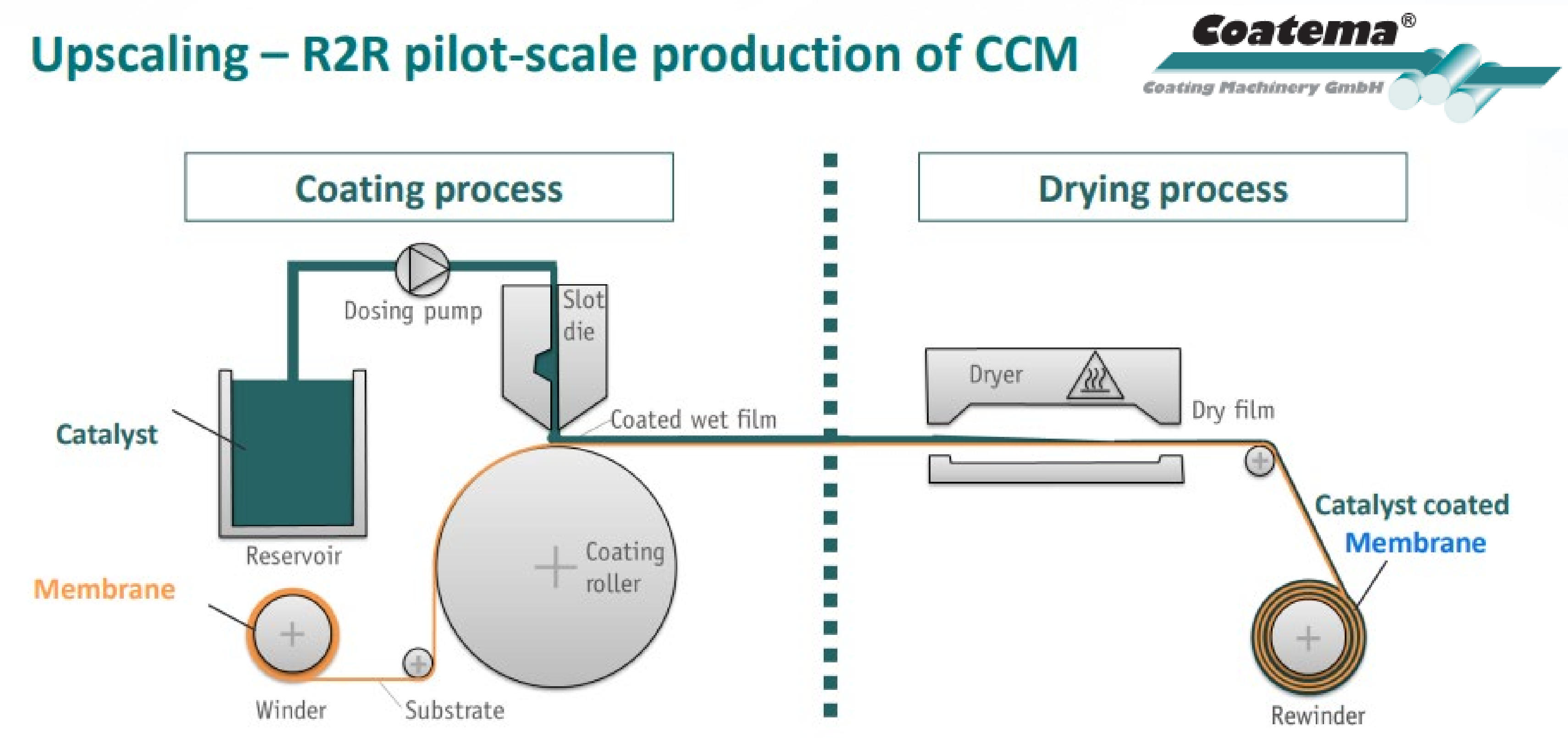
Based on:

- 275 kW_{net} HDV systems
- 2022 & 2025: 4 stacks/sys
- 2030: 2 stacks/sys

Membrane Electrode Assembly (MEA)

- Fabrication of (most) sub-components well-suited to R2R production
  - GDL, membrane (supported/not-supported), catalyst layer deposition, sheet gaskets
    - All have established R2R production processes
  - Exception: PTL (porous Ti, or alterative)
    - Less clear that R2R is best production route
- Assembly of MEA Components
  - Manual assembly
    - Currently used for (some) FC, (most/all) electrolyzers
    - Slow, labor intensive (by definition), accuracy and error-rate concerns
  - Pick & Place
    - Multiple equipment vendors developing systems
  - R2R (really Roll-to-Piece)
    - Prototype and First-Full-Systems are under development

Catalyst Application Well-Suited to R2R (slot-die) Processes

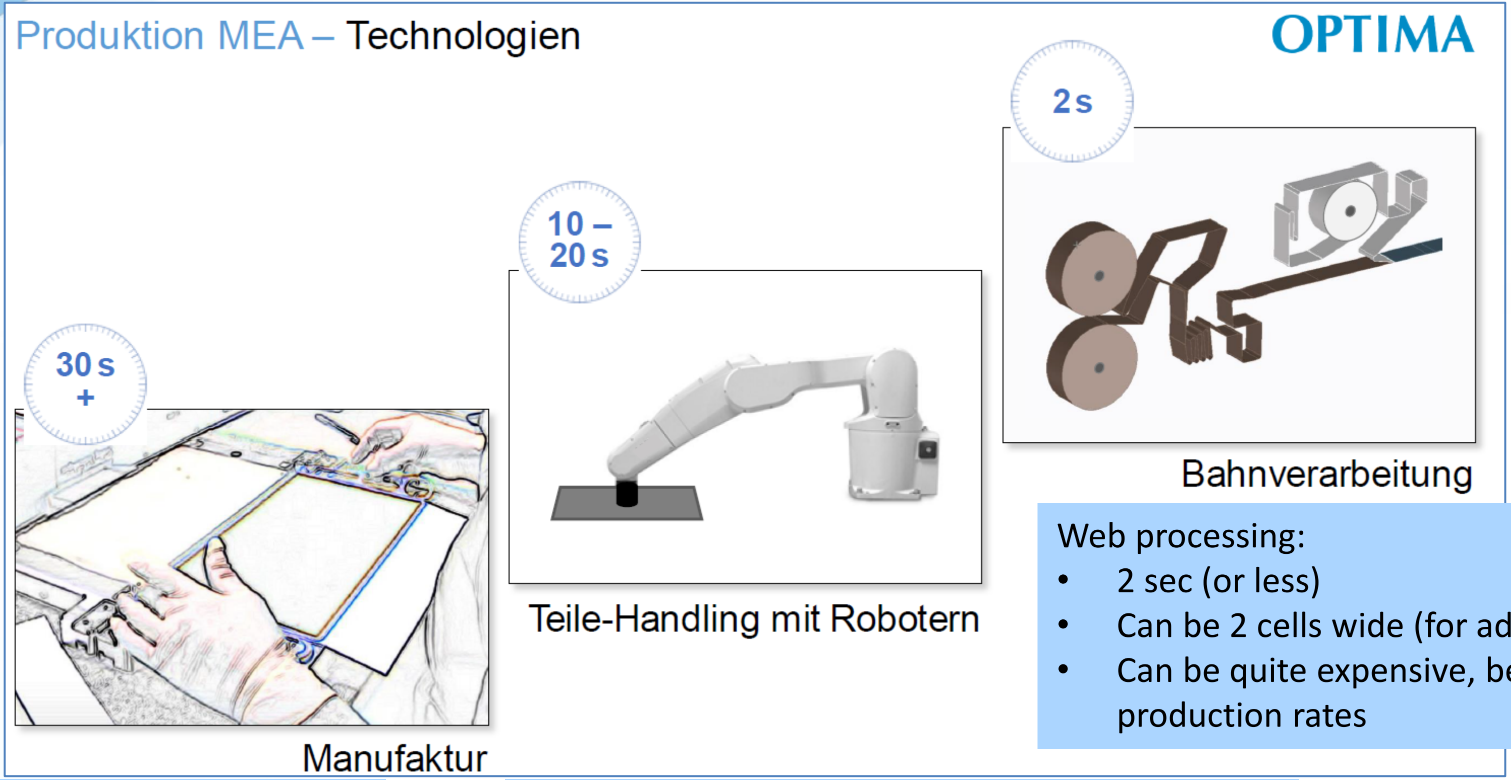


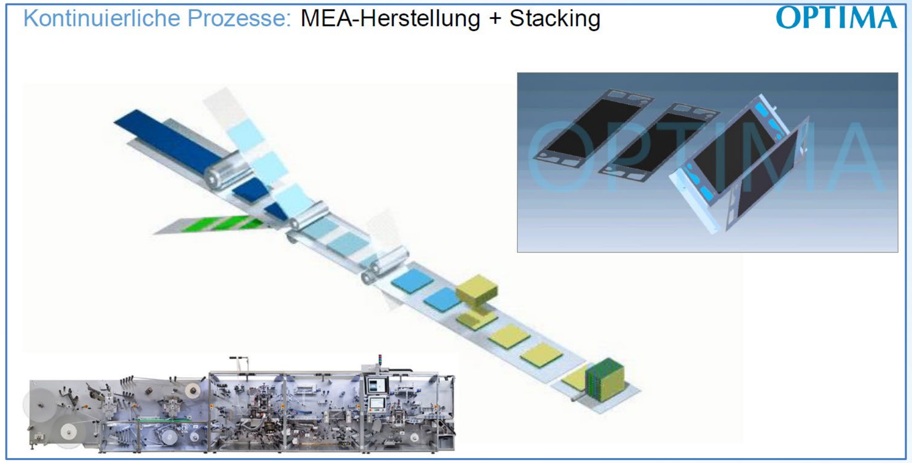
- 10 m/min (faster speed requires more expensive stable materials)
- Continuous or patch coating
- Apply directly to membrane or onto carrier sheet (for subsequent decal-transfer to membrane)
- Other catalyst application options:
  - Ultra-sonic spray
  - Other

- **RD&D Issues/Desires:**
  - Higher speed
  - Lower capital cost
  - Ink formulations for high speed
  - Wider widths
  - Modularity
  - Design flexibility
  - In-line QC
  - Registration of defects

https://www.now-gmbh.de/wp-content/uploads/2021/08/Marktplatz-Zulieferer_Technology-development-and-manufacturing-for-fuel-cells-and-electrolyzers_Kolbusch.pdf

MEA Assembly Options





Web processing:
- 2 sec (or less)
- Can be 2 cells wide (for added cost)
- Can be quite expensive, best for high production rates

Manual:
- 15-30 seconds/part

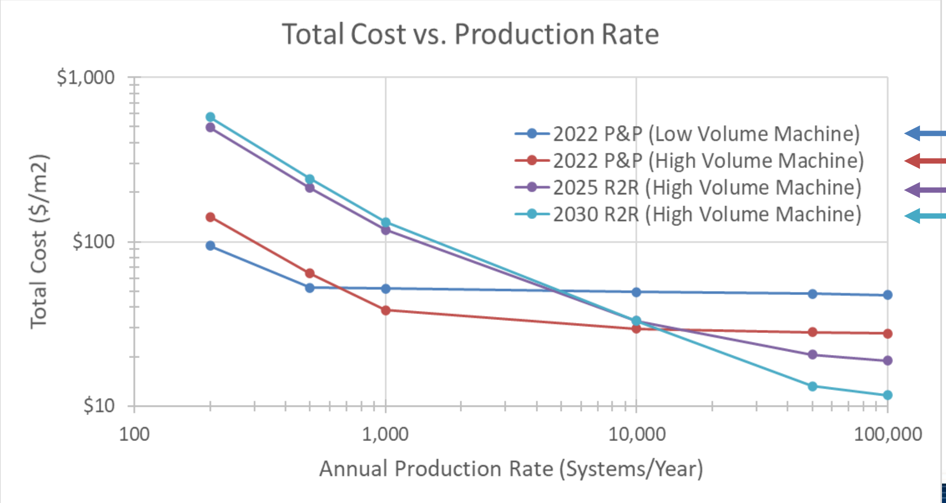
Robots for parts handling:
- Anthropomorphic/Articulated-Arm: 4-8 sec SOA, often 10+ sec
- SCARA: <1 sec
- Delta: <1 sec
- Accuracy influences speed
- Dual/Alternating robots can cut time in half

Source: Optima https://www.now-gmbh.de/wp-content/uploads/2021/08/Marktplatz-Zulieferer_Effiziente-Produktion-von-Komponenten-fuer-Brennstoffzellen_Volk.pdf

SA Cost Modeling of MEA Assembly

- **<u>7-layer MEA ("Gasketed MEA", UMEA)</u>**
  - Roll-to-Piece line
  - Input: rolls of CCM, Gasket, GDL
  - Output: discretized UMEA
- Further mid-volume production solutions to be explored (e.g., simplified R2R)

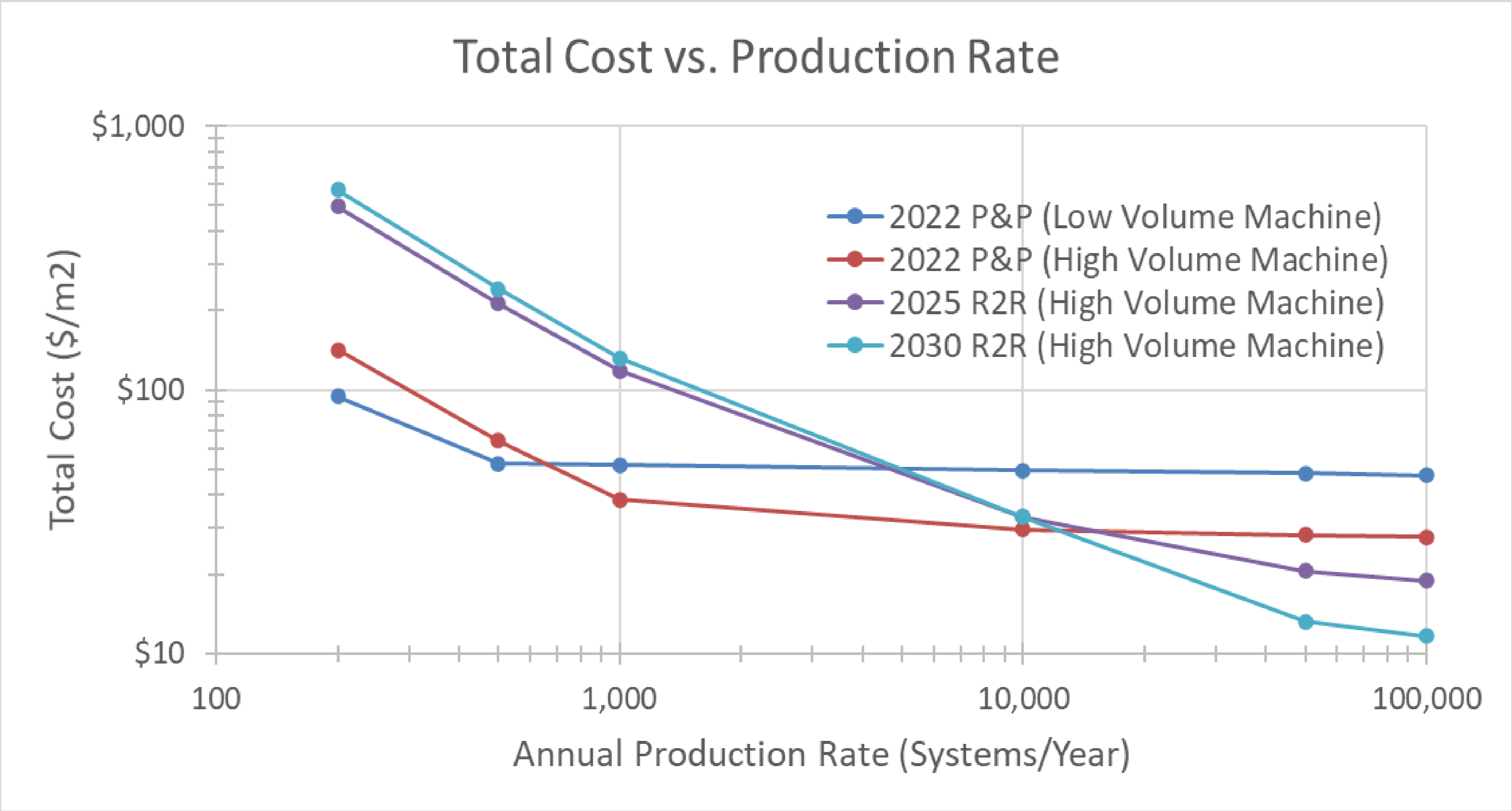
Basis: 55/46/37 m2/sys (2022/2025/2030), 275kW/sys



Year	2022			2025			2030		
Production Rate (Systems/Year)	Low1	Med1	High1	Low2	Med2	High2	Low3	Med3	High3
Stacking Method	P&P	P&P	P&P	P&P	P&P	R2R	P&P	P&P	R2R
Line Speed (m/min)						15			25 (vendor target)
Max Width (mm)						650 (vendor spec.)			650
Max Parts Across Width						1			2
P&P Time Per Part (sec/part)	5 (vendor spec.)	5 (vendor spec.)	5	5	5		4	4	
Parts Per Cell	6	6	6	6	6		6	6	
P&P Time Per Cell (sec/cell)	30	30	30	30	30		24	24	
Simultaneous Robots	2	6	6	2	6		2	6	
Effective Time Per Cell (sec/cell)	15 (vendor spec.)	5 (vendor spec.)	5	15	5	0.71	12	4	0.27
Capital Cost ($/line) (cost basis)	$1.7M (Vendor ROM)	$3.1M (~vendor spec.)	$3.1M (Vendor ROM)	$1.4M (= Low1 −15%)	$2.6M (= Med1 −15%)	$9.4M (Vendor ROM)	$1.2M (= Low2 −15%)	$2.2M (= Med2 −15%)	$8.7M (= High2 −6.5%)

- Technology advances projected for 2025/2030 (speed, design)
- Cost advances projected for 2025/2030 (based on design advances, and increased prod. vol.)

SA Preliminary Selections for MEA Assembly (2022, 2025, 2030)



Based on:

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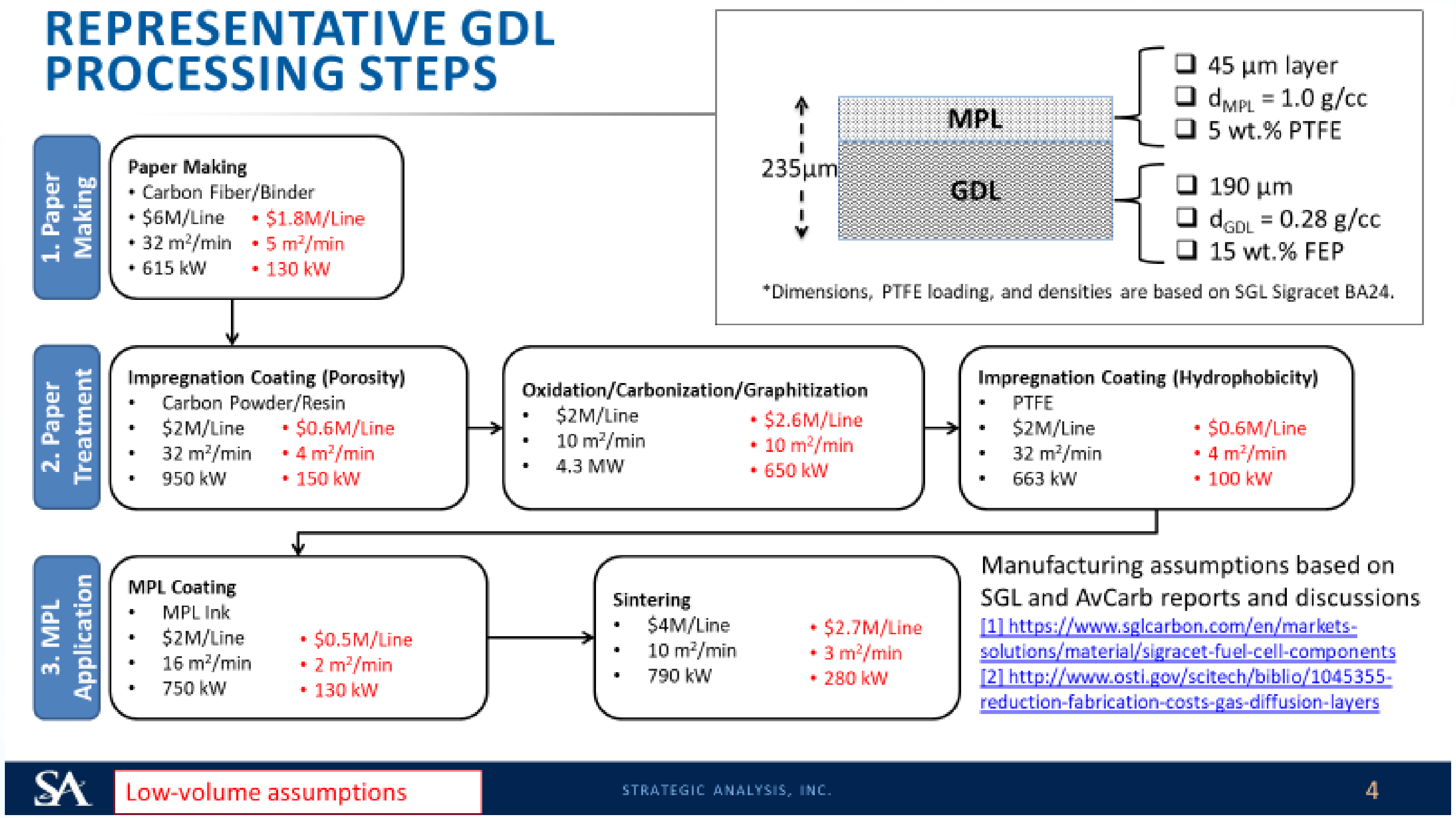
Manufacturing Outlook for GDL

- Major suppliers are globally distributed: Teijin and Toray (Japan), Freudenberg and SGL (Germany), Avcarb (US)
- Patent filings appear to be dominated by system integrators and OEMs
- E4tech industry review (https://fuelcellindustryreview.com/) reported 1.03 GW PEMFC deployed in 2020, which suggests an annual GDL market of 90,000 m^2 to 170,000 m^2 (assuming 600-1200 mW/cm^2)
- A plant production of 100k 300 kW HDV systems per year would need ~12M m^2 of GDL



“Low volume” plant can supply 1.6M m^2/year (~4 GW, ~13k HDV) at 100% plant capacity

“High volume” plant can supply 10x at 100% plant capacity, (17M m^2/year, 42 GW/year, 130k HDV)

- High volume plants coming online 2022

Houchins, James, Huya-Kouadio. “Gas Diffusion Layer (GDL) Manufacturing Needs for Clean Hydrogen Technologies Workshop”, 19 April 2022

Leak Testing and Conditioning

- As manufacturing yield improves, <100% part testing may be acceptable
- Scale-up to higher simultaneously tested parts reduces effective cycle time (effective seconds/part)
- Improved high-speed loading & unloading
- Leak test cycle time optimization expected to reduce times (alternative gases)
- Stack conditioning generally has a goal of 1 hour (MEA/stack supplier specific)

Leak Test Scope	Objective	Advantage of Testing this Component	Typical Test Time	Potential for Improvement
BPP	• Test for proper sealing of the BPP	• Typically inline with production	10s	• As defects decline, 100% part testing may not be needed
MEA	• Test for perforations or other manufacturing deformities	• Typically inline with production	1-3s	• As defects decline, 100% part testing may not be needed
Cell (MEA & BPA)	• Test 3 flow channels (hydrogen, air, and coolant)	• Can rapidly reject cells with poor leak performance	120s-180s	• Alternative/Faster testing gases e.g. Forming Gas (H_2 and N_2) • As manufact. yield improves, may elect to omit this leak test
Partial Cell Stack	• Test 3 flow channels (hydrogen, air, and coolant) over multiple cells	• More economically test bundles of cells as opposed to individual cells	120s-180s	• Alternative/Faster testing gases e.g. Forming Gas (H_2 and N_2) • As manufac. yield improves, may elect to omit this leak test
Full Cell Stack (Leak Test)	• Test 3 flow channels (hydrogen, air, and coolant) of full stack	• As confidence of manufact. quality rises, this level of cell testing may be sufficient	120s-180s	• Alternative/Faster testing gases e.g. Forming Gas (H_2 and N_2) • Can use cell level "sniffer" to detect leaks from indiv. cells
Full Cell Stack (Conditioning)	• Break in and performance testing of fuel cell stack	• Performance of fuel cell improves over the break-in period	~2-8 hours (~2.5 h most common)	• Preconditioning of partial cell stacks may improve the testing time of the final conditioning step • Since break-in continues during initial usage by customer, manufacturers may elect to reduce their break-in time as initial fuel cell performance improves

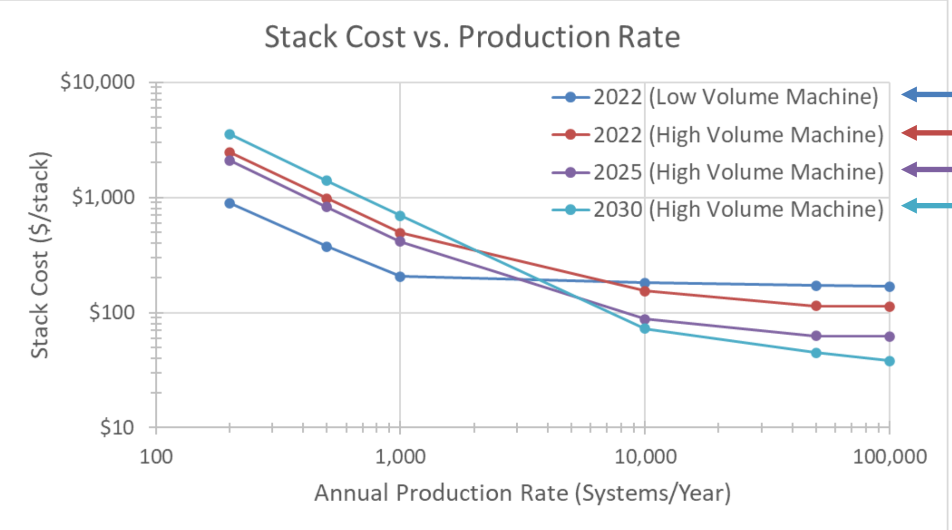
SA Cost Modeling of Stack Conditioning

- **Stack Conditioning**
  - Electrical Continuity/Factory-Acceptance-Test (FAT)
  - "Conditioning" with steam and electrical load bank
  - (Optional) Stack Leak Test

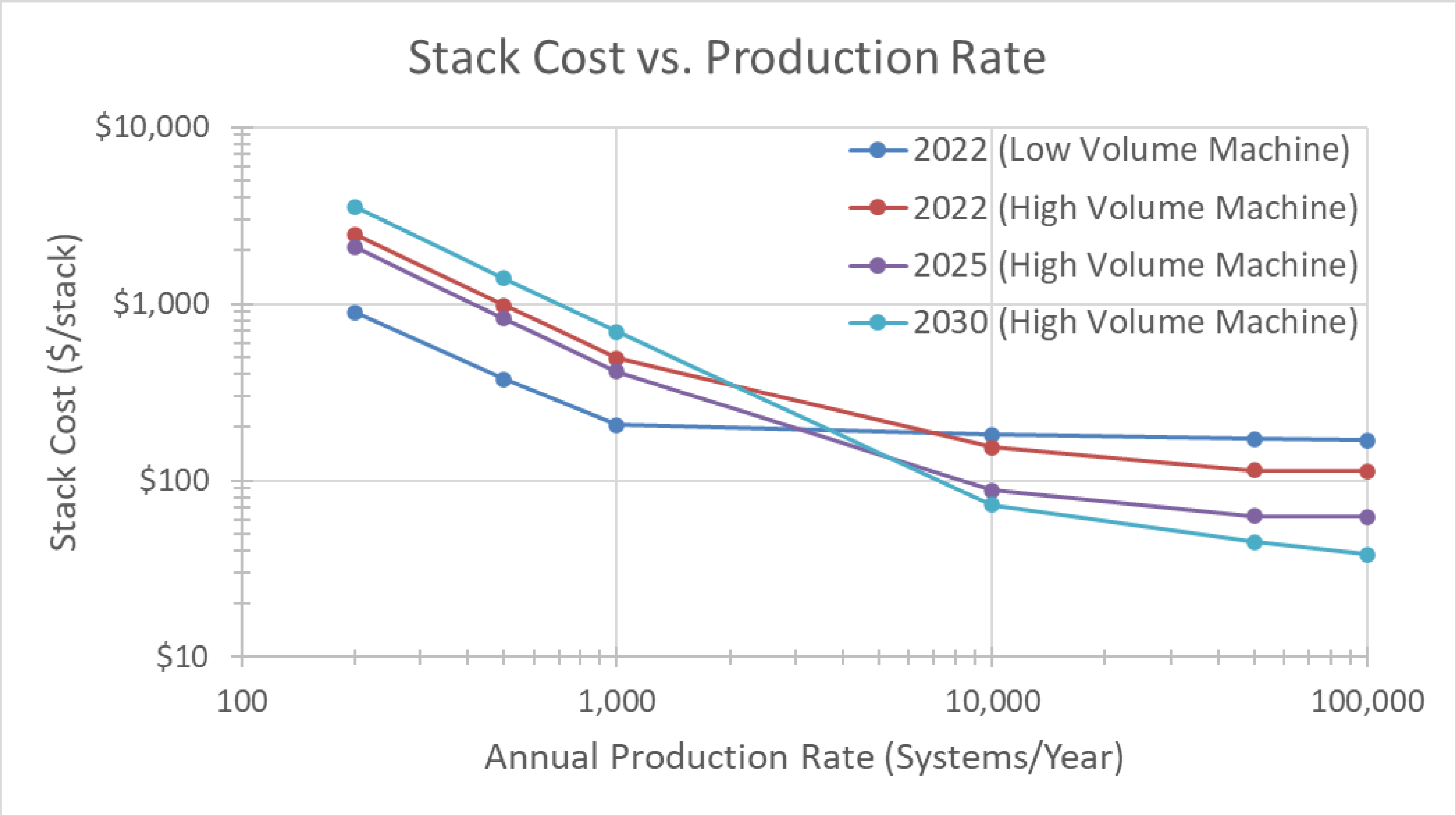
Prelim. RD&D Issues/Desires:

- Optimized/shorter conditioning time
- Multiple stack simultaneous testing
- Reduced capital cost
- Creative ways to recycle gases/electricity

Year	2022			2025			2030		
Production Rate (Systems/Year)	Low1	Med1	High1	Low2	Med2	High2	Low3	Med3	High3
Conditioning Time Per Stack (hr/stack)	2.5 (2-8+, 2.5 typical)	2.5	2.5	1.5	1.5	1.5	1 (vendor target)	1	1
Stacks Tested Simultaneously	2	4	8	2	4	8	2	4	8
Capital Cost ($/line)	$1.4M (Vendor ROM)	$2.3M (= Vendor ROM +70%)	$4M (= Med1 +70%)	$1.2M (= Low1 −15%)	$2M (= Med1 −15%)	$3.4M (= High1 −15%)	$1M (= Low2 −15%)	$1.7M (= Med2 −15%)	$2.9M (= High2 −15%)



Stack Conditioning Cost Comparison



Based on:
- 275 kW_{net} HDV systems
- 2022 & 2025: 4 stacks/sys
- 2030: 2 stacks/sys

Summary and Key Take-Aways

- Cycle time and Capital Cost are key drivers
  - Suggest “Sec/part” and “Cap Cost $/stack-processed” as automation metrics
- Desire flexibility to produce various FC/Electrolyzer products with a single line
- Need high-speed, in-line quality control
- Should learn lessons from Battery manufacturing
- Current/Future automation offer Digitalization and 100% part-tracking
- Web registration and ability to tracking defects through process line is planned/contemplated
- Pick & Place robots and R2R systems both have their strengths and best applications
- Assembly increasingly integrated (in sense that processes are combined into single lines e.g., stacking, leak test, compression/banding)
- Many ancillary processes are conceptually low-risk but will take effort to demonstrate/develop for their specific FC/electrolyzer application

Thank you!

Questions?