

RESEARCH ARTICLE OPEN ACCESS

Techno-Economic Assessment of Manufacturing Membrane Electrode Assemblies for PEM Fuel Cells: Focus on Coating Technologies

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ABSTRACT

High manufacturing costs of proton exchange membrane (PEM) fuel cells remain a significant obstacle to their widespread adoption in transportation applications. To address this, roll-to-roll (R2R) processes are proposed to increase production throughput and reduce membrane electrode assembly (MEA) costs. Among R2R-compatible coating processes, slot-die coating (SDC) represents the state-of-the-art technology, while rotary screen printing (RSP) offers advantages in structured and intermittent printing, providing additional design freedom for catalyst layers (CL). This study examines the cost implications of both coating processes for a specific set of R2R machines to be implemented at Fraunhofer ISE. Technical boundary conditions and operational limitations are evaluated and integrated into a comprehensive continuous process cost of ownership model capturing expenses throughout the production chain, from catalyst ink raw materials to the final seven-layer MEA. A methodology is presented for determining consumable costs at various purchasing volumes, combining literature values with supplier quotations. By integrating performance data from experimentally produced MEAs with the cost model, an approach is developed to determine optimum platinum (Pt) loadings for cost per kW for given materials. The identified optimal Pt loadings of $0.44\text{--}0.54\text{ mg Pt cm}^{-2}$ demonstrate that the cell performance is crucial for further cost reductions of fuel cells.

1 | Introduction

It is widely acknowledged that increasing the manufacturing volume reduces the cost of a final product [1]. However, the critical question centers on identifying precisely where these cost savings emerge within the manufacturing process chain and what insights can be derived to further optimize the product design. For proton exchange membrane fuel cells (PEMFCs), this understanding is particularly valuable since the membrane electrode assembly (MEA) remains one of the dominant cost drivers in a complete stack [2].

While large-scale deployment remains limited by high costs, low-temperature PEMFC are widely recognized as a key low-

emission technology for decarbonizing the transport sector, which accounts for approximately 20% of global CO₂ emissions [3, 4]. Special focus is placed on PEMFCs for heavy-duty vehicles, as in Europe they contribute a disproportionate 23% of transport emissions while representing only 2% of all vehicles [5, 6].

Despite achieving technical maturity at laboratory scale, the large-scale market penetration of PEMFCs continues to face economic and production-related challenges [7, 8]. The MEA represents the core component and requires costly as well as specialized materials like platinum-based inks and perfluorosulfonic acid membranes. These inks are processed into catalyst layers (CL) using various coating and printing techniques such as slot-die coating (SDC), spray coating, inkjet printing, gravure

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Impact of Coating Technologies on the Production Cost of PEM Fuel Cells

Speaker: Jakob Hog

Co-authors: Diego Matali Goya, Julius Wild, Linda Ney, Nada Zamel, Ulf Groos

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Freiburg, Germany, 29.04.2026

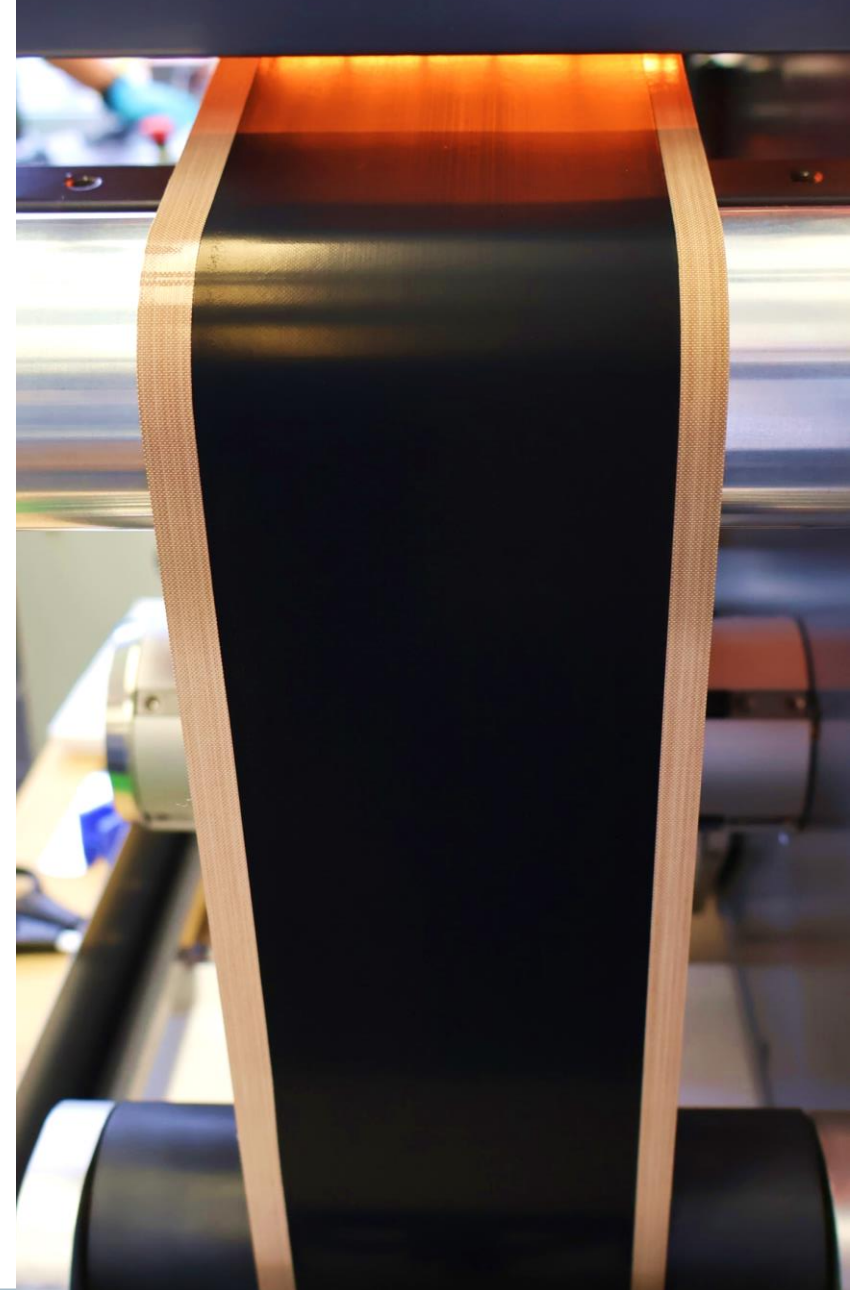
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Impact of Coating Technologies on the Cost of PEMFC

Agenda

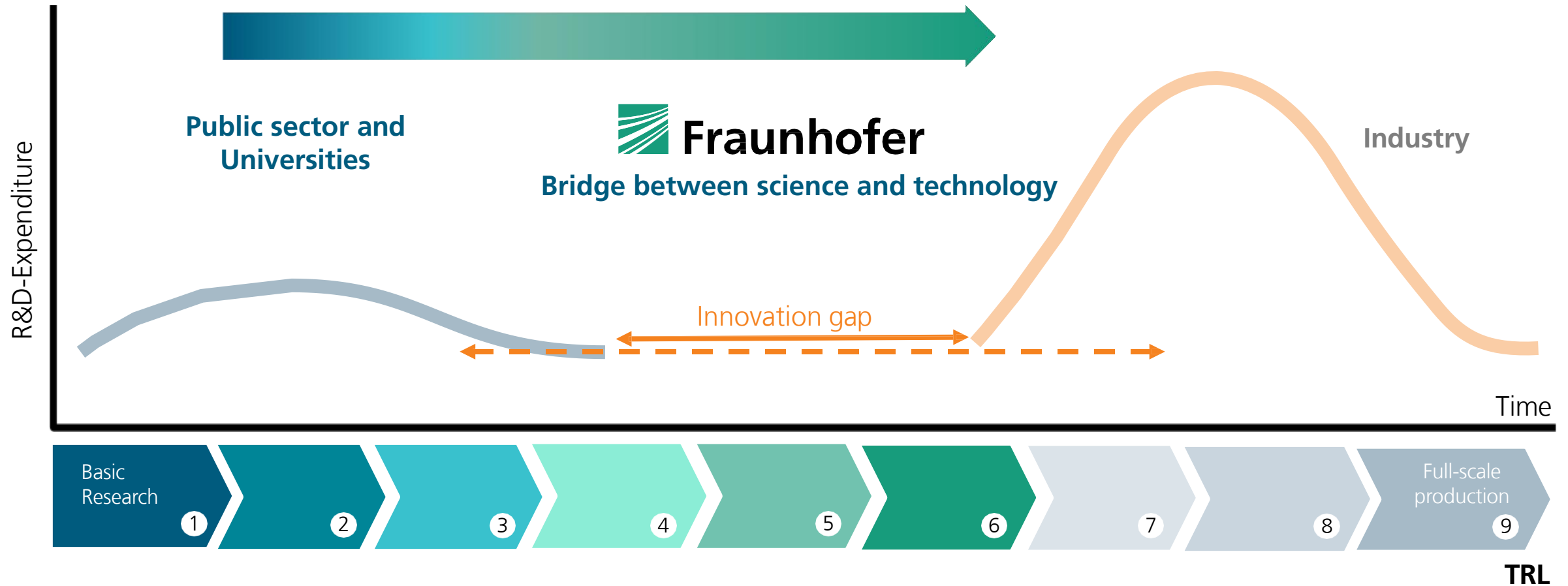
1. Scenario Description
2. Consumable Cost Modeling
3. CCM Fabrication
4. MEA_{7L} Fabrication
5. Performance Sensitivity



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Our Mission in Our Department Fuel Cell

Assisting Global Industry with Scientifically Sound Services

Understanding Fuel Cell Membrane Electrode Assemblies (MEAs)

Key Performance Indicators 2024:

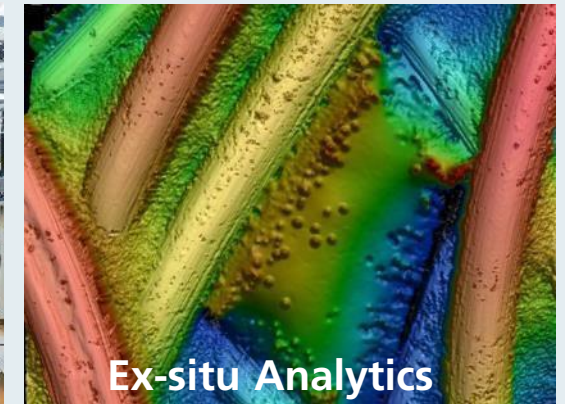
- 45 researchers plus students
- 9.2 Mio. € annual budget (w/o investments)
- 33% direct revenue by industry contract research
- > 500 m² laboratory area with 13 single cell test stations, 5 short stack test stations including temperature chamber (all fully automated for 24/7 operation)
- Focus on transport application

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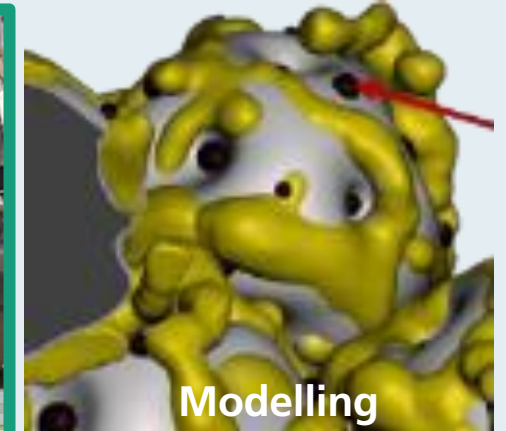
In-situ Characterization



Ex-situ Analytics



Production Research



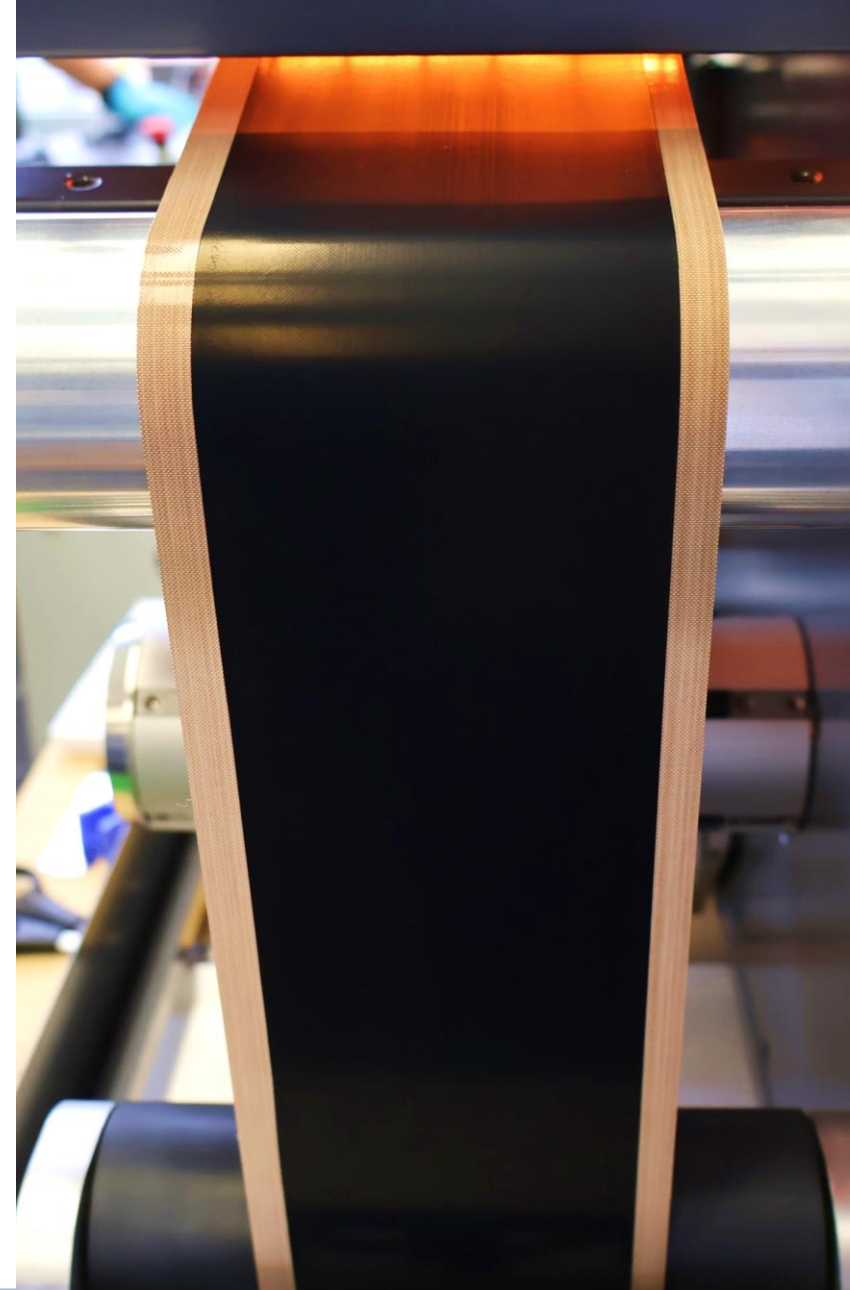
Modelling

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Impact of Coating Technologies on the Cost of PEMFC

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2. Consumable Cost Modeling
3. CCM Fabrication
4. MEA_{7L} Fabrication
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Scenario Description

Consumable Cost Modeling

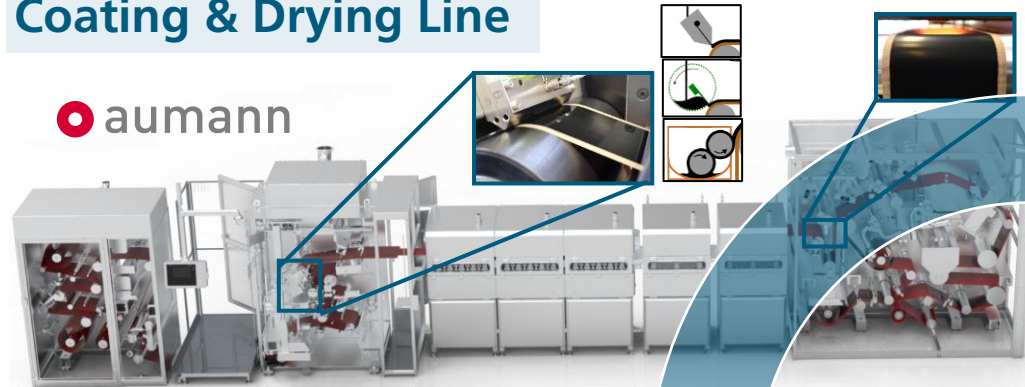
CCM Fabrication

MEA_{7L} Fabrication

Performance Sensitivity

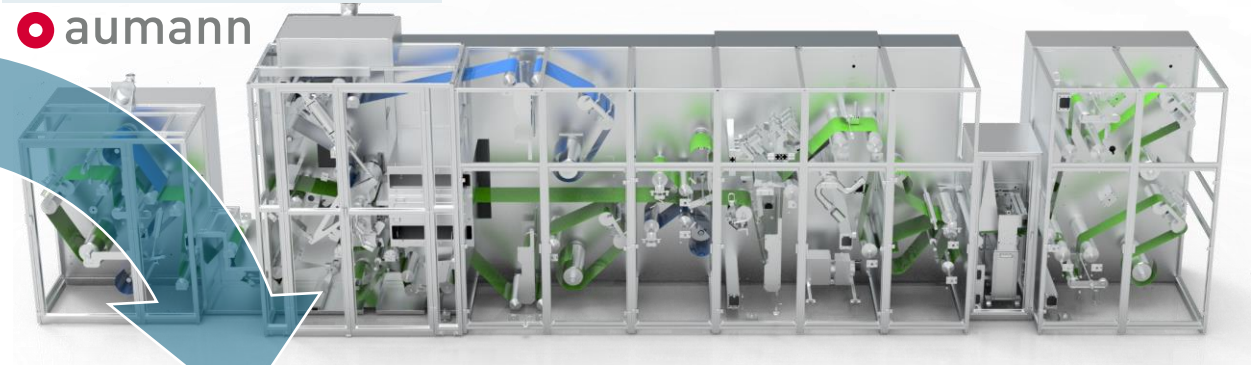
Coating & Drying Line

• aumann



CCM Transfer Line

• aumann



Ink Mixing

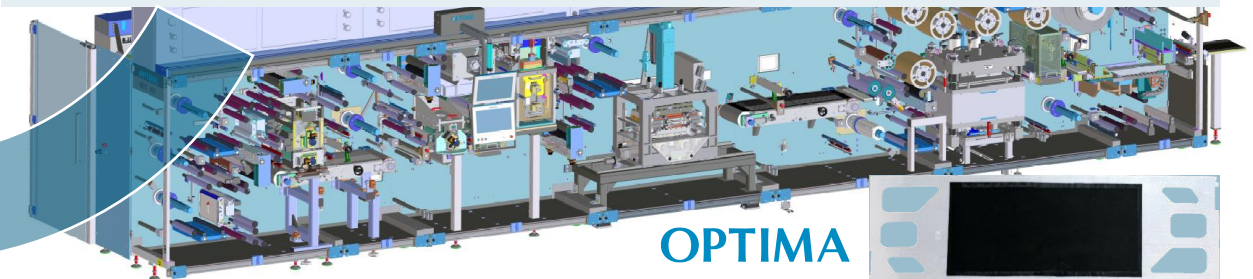
IFA
TECHNOLOGY

Member of Deuretech Group



R2R production research

CCM & GDL Cut, Subgasket Lamination, 5-Layer MEA



OPTIMA

Scenario Description

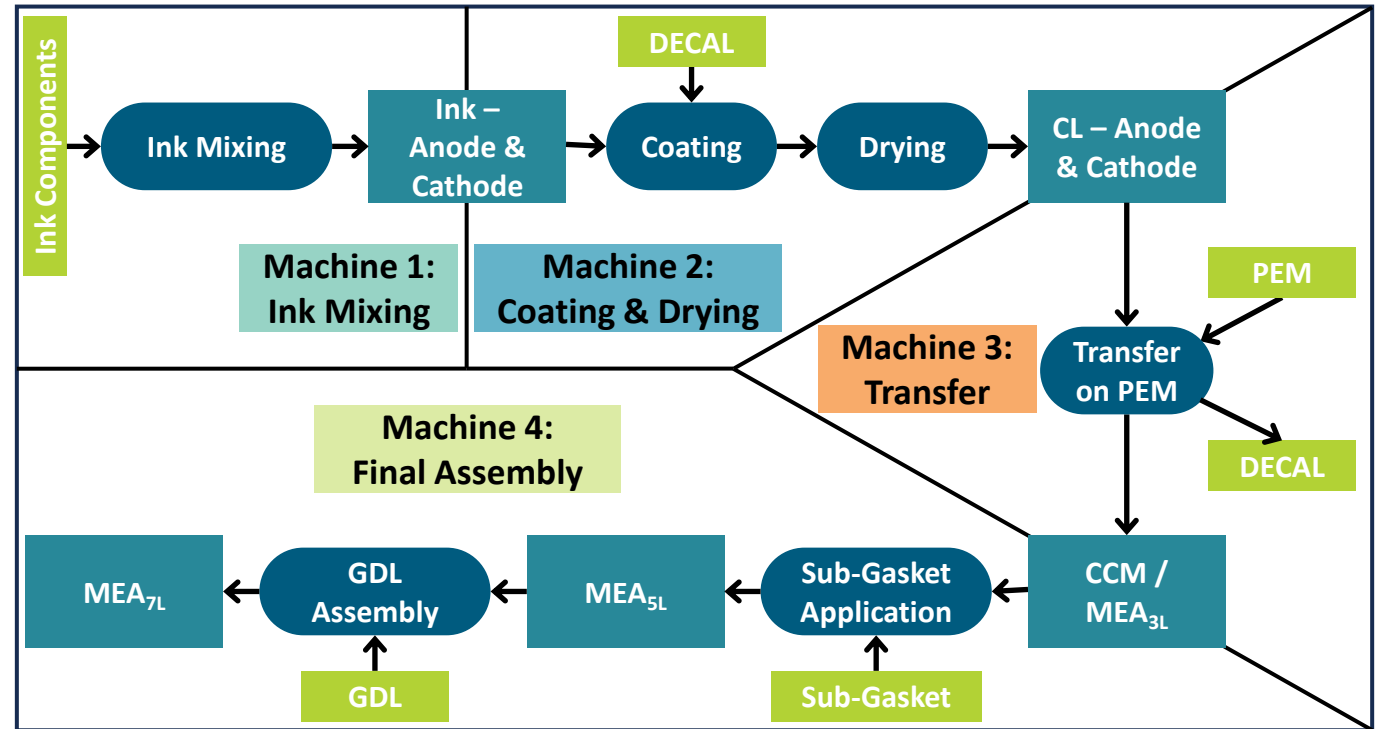
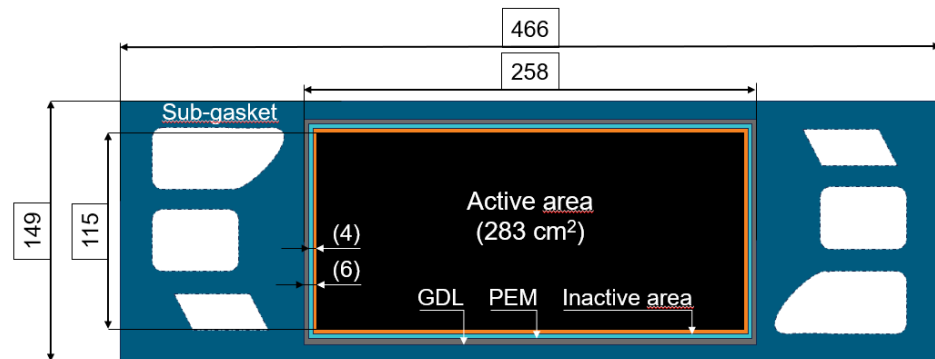
Consumable Cost Modeling

CCM Fabrication

MEA_{7L} Fabrication

Performance Sensitivity

Production Scenario (Pilot Plant)		Research	Industry
Production time	working days per year *	251 – 8h	355 – 24h
	Spliced PEM rolls (250m)	n 1-2	n 1-5
Process Yields:	Ink Loss *	1 L	1 L
	CCM Yield ^[1]	91 %	94 %
	GDL Yield ^[1]	96 %	99 %
	Sub-Gasket Yield ^[1]	98 %	99.5 %
MEA design		Generic Stack ZSW ^[2]	

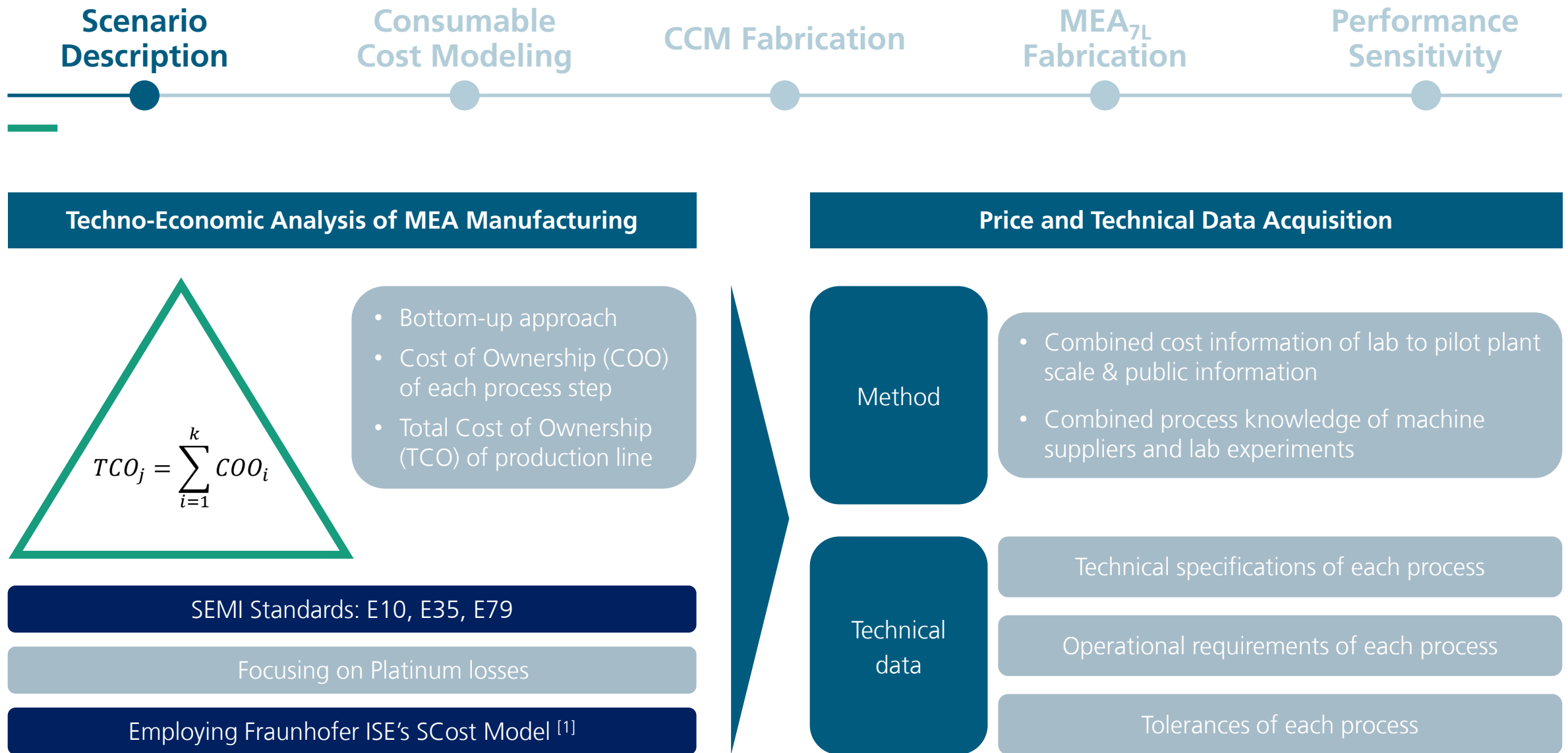


➤ How do the scenarios affect the cost of the MEA_{7L}?

* Assumption

[1] Wei M et al. (2019): Fuel Cell Systems, Total Cost of Ownership. In: Meyers RA, editor. Encyclopedia of sustainability science and technology. New York, NY: Springer, p. 1–56.

[2] Adapted of “[Manufacturer-independent fuel cell stack: an innovative development platform for industry and science](#)”, ZSW, accessed July 2024

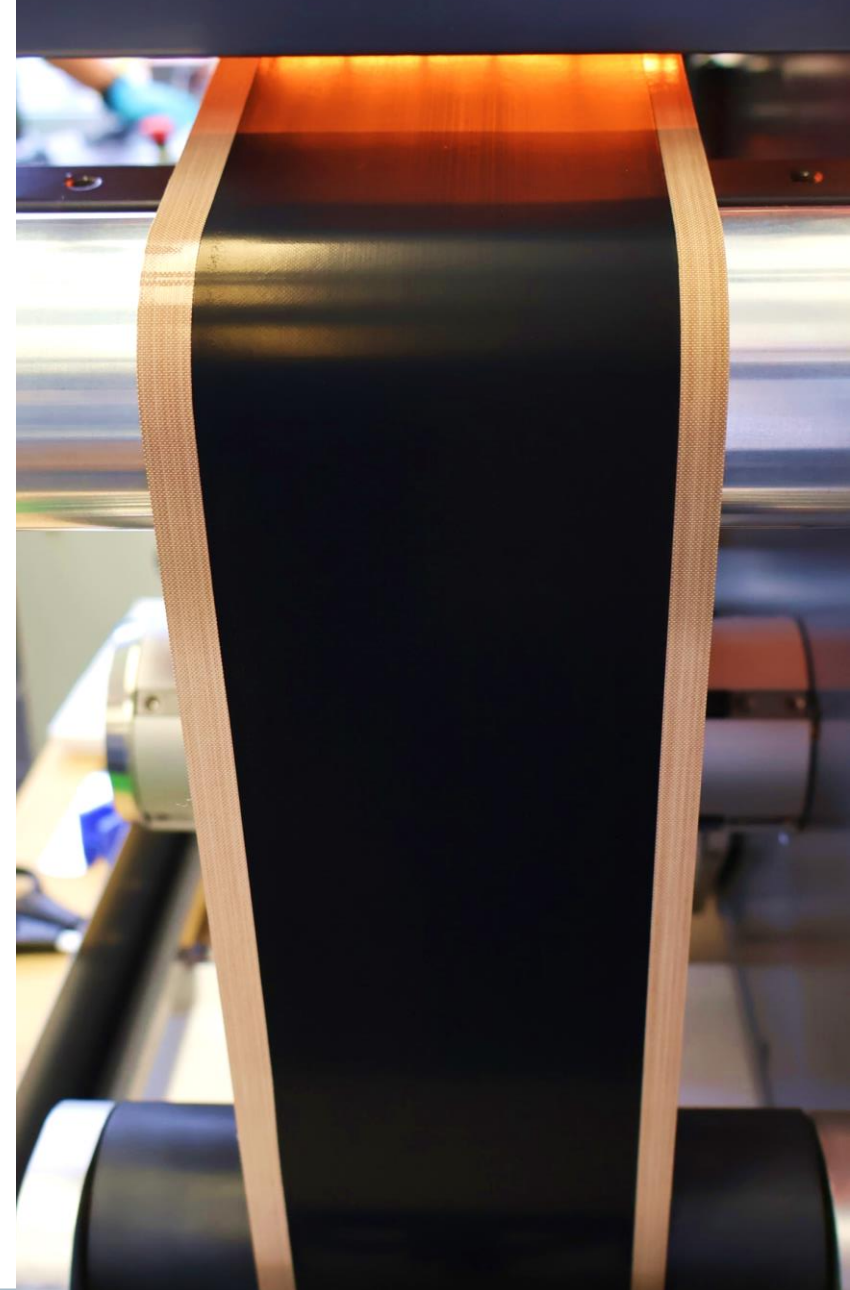


[1] Nold, Sebastian (2019): Techno-ökonomische Bewertung neuer Produktionstechnologien entlang der Photovoltaik-Wertschöpfungskette. Dissertation

Impact of Coating Technologies on the Cost of PEMFC

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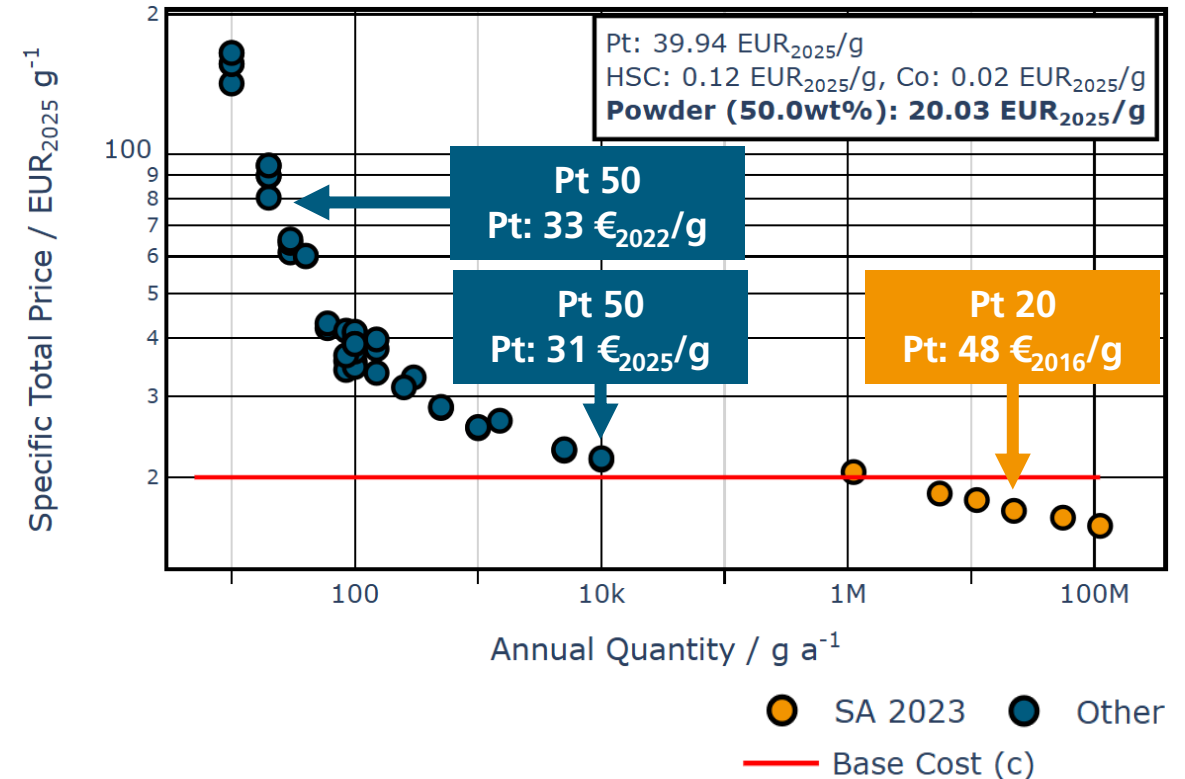
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General Learning Curve – Price Degression:

- $T(R) = a * R^b + c$ ^[1]
 - **T:** *Specific Total Price*
 - **c:** Material prices only (Scenario / Offer specific)
 - **a, b:** *Specific Process Cost* (defined by dataset)
 - Includes Markup, Processing, ect.
 - **R:** Purchase quantity from one manufacturer

Cathode Catalyst Powder

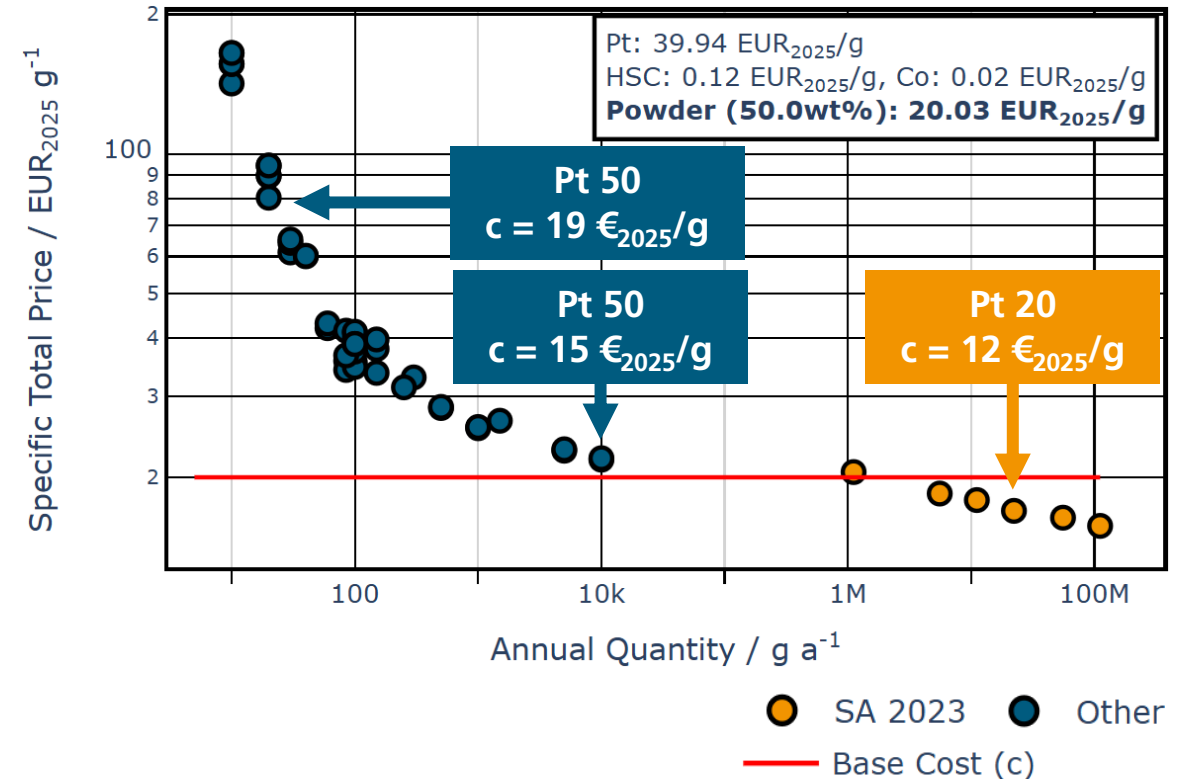


[SA 2023] James et al. (2023): DRAFT: Mass Production Cost Estimation of Direct H₂ PEM Fuel Cell Systems for Transportation Applications: 2023 Update on Heavy-Duty and Medium-Duty Vehicles.

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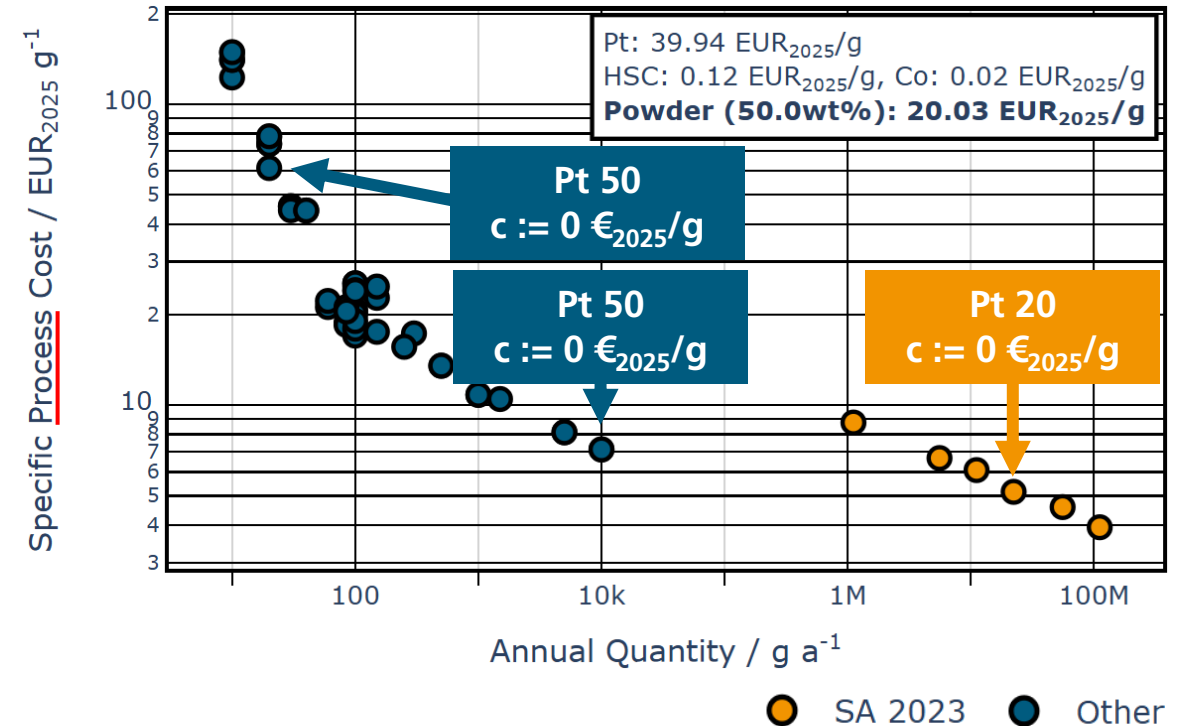


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Fitting of the model parameters:

- Log Transformation of the function and data
- Linear Regression: Scikit-learn [2]

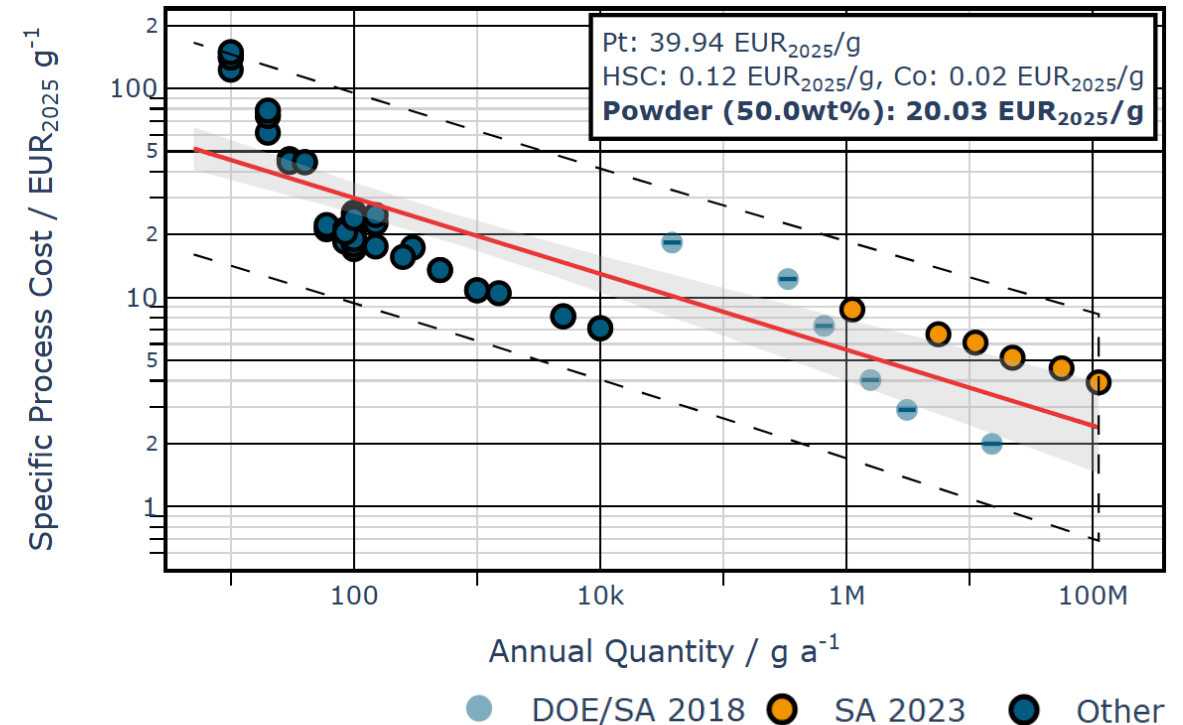
[DOE/SA 2018] James et al. (2018): Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications: 2018 update.

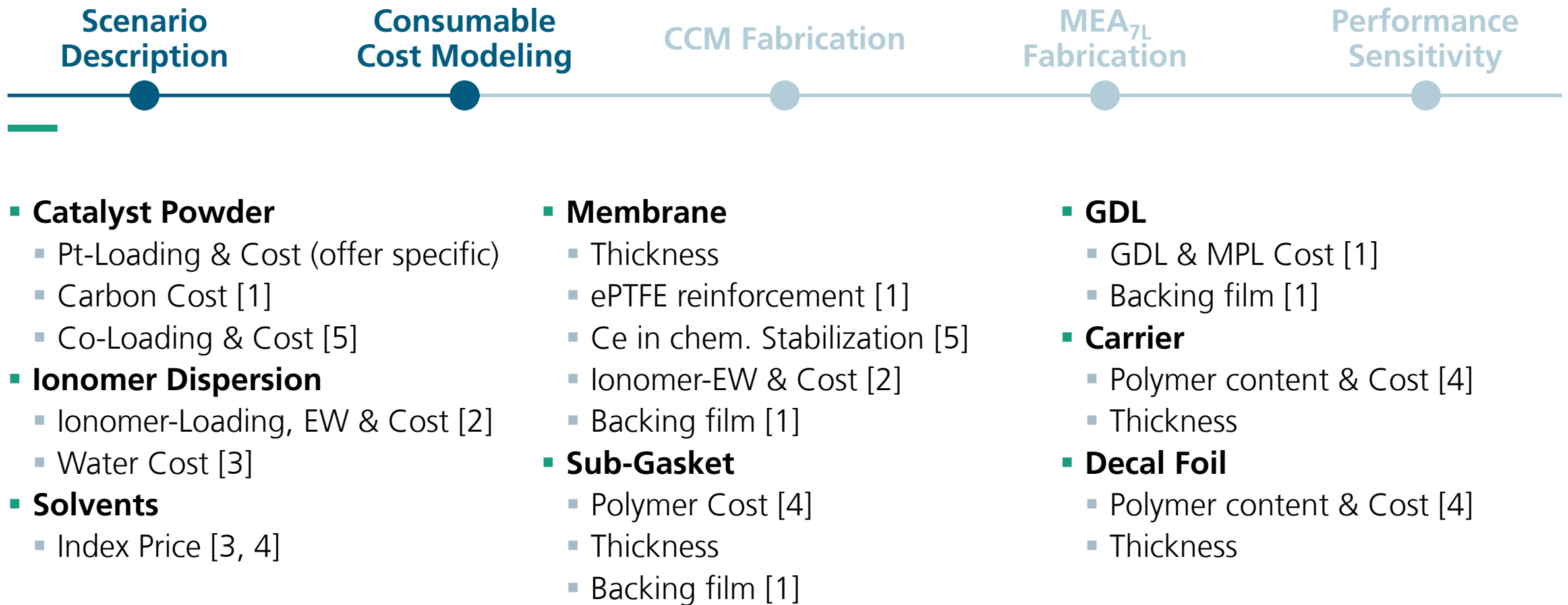
[SA 2023] James et al. (2023): DRAFT: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2023 Update on Heavy-Duty and Medium-Duty Vehicles.

[1] Lam F. Wong (2012): A Generalized Learning Curve Adapted for Purchasing and Cost Reduction Negotiations.

[2] Pedregosa et al. (2011): Scikit-learn: Machine Learning in Python. In: Journal of Machine Learning Research 12, S. 2825–2830.

Cathode Catalyst Powder





- [1] James et al. (2018): Mass production cost estimation of direct H₂ PEM fuel cell systems for transportation applications: 2018 update.
 [2] Bernhart et al. (2014): Fuel Cells - A Realistic Alternative for Zero Emission? Auto Tech Review;3(3):18–23.
 [3] Kwon et al (2018): The Estimation of Total Cost Through the Financial Assessment of Customized High Purity Industrial Water. J Korean Soc Environ Eng;40(11):428–37.
 [4] <https://businessanalytiq.com/procurementanalytics/index/>
 [5] <https://www.statista.com>

➤ **275 Data points**
 ➤ **24 Companies**

Scenario
Description

Consumable
Cost Modeling

CCM Fabrication

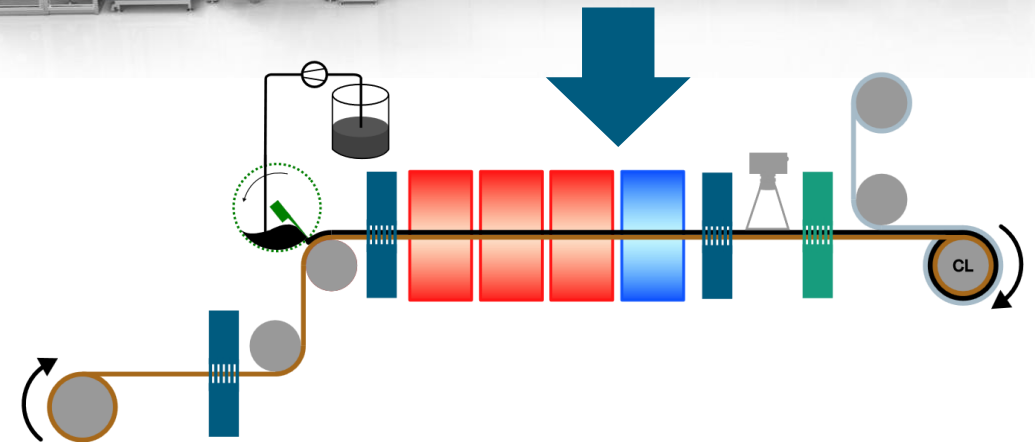
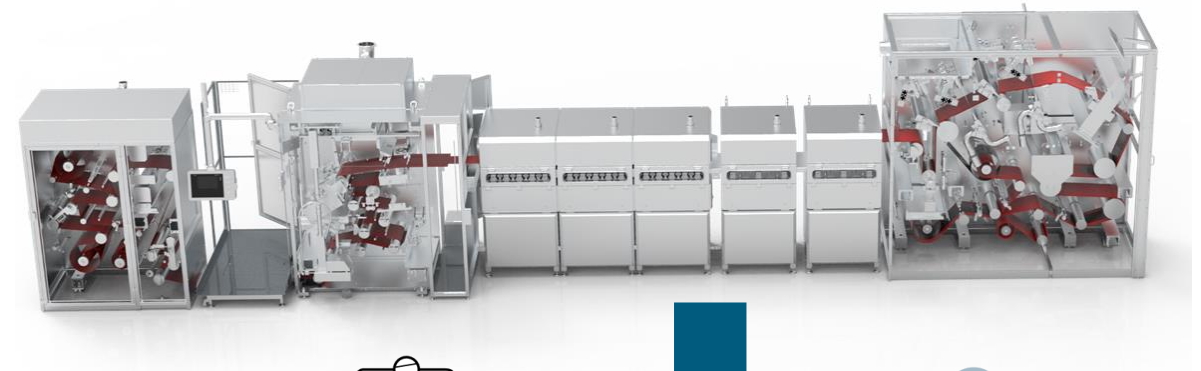
MEA_{7L}
Fabrication

Performance
Sensitivity

Conclusion

- **Material based consumable modeling** for flexible scenario variation
 - Throughput | Material composition

Machinery at Fraunhofer ISE

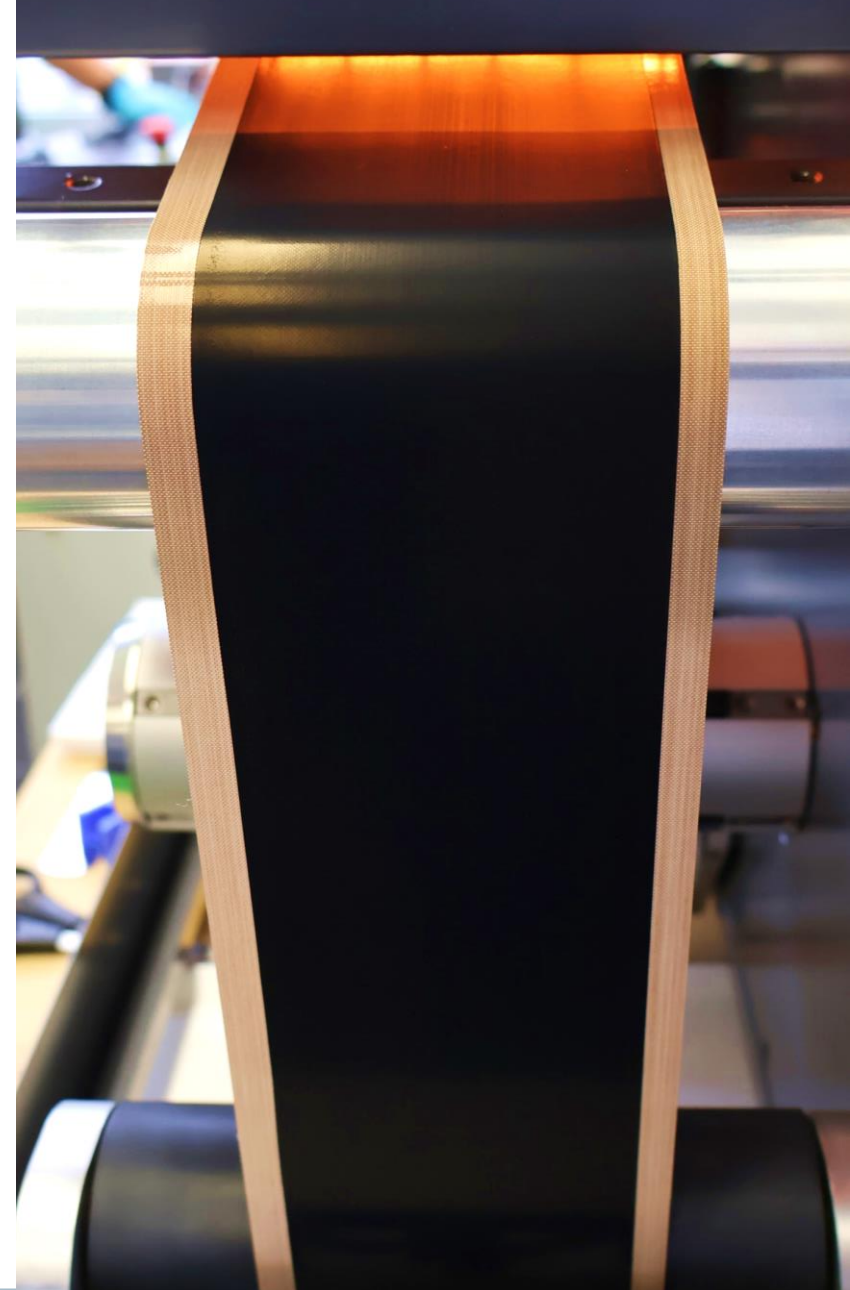


Comprehensive Cost Model

Impact of Coating Technologies on the Cost of PEMFC

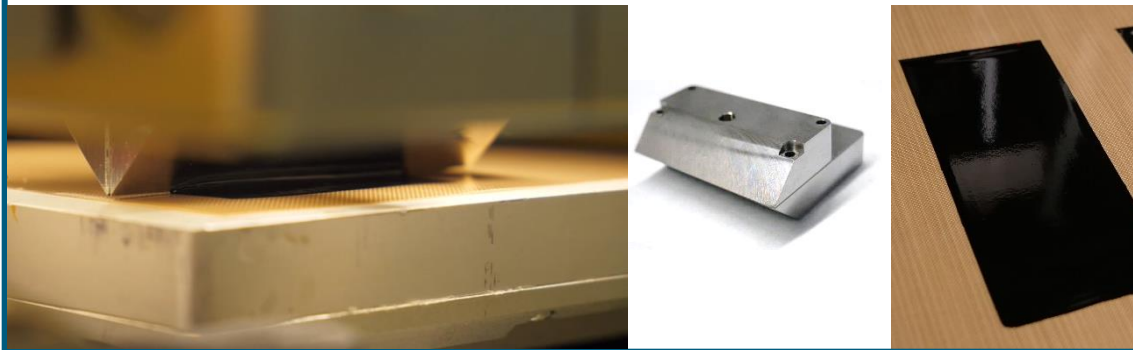
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Slot Die Coating

- Control of wet layer thickness by volume flow and velocity
- Ink inside a closed ink reservoir
- Less flexible structure of the coated layer
- Intermittent & continuous coating possible in R2R



Screen Printing

- Control of the wet layer thickness by choice of screen thickness
- Ink exposed to air during printing process
- More degrees of freedom to apply structures
- Adaptable to R2R process with rotary screen printing



Scenario Description

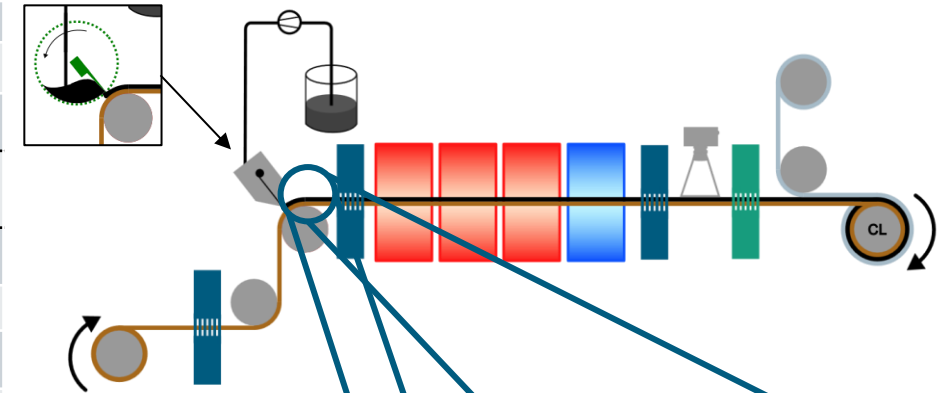
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CCM Fabrication

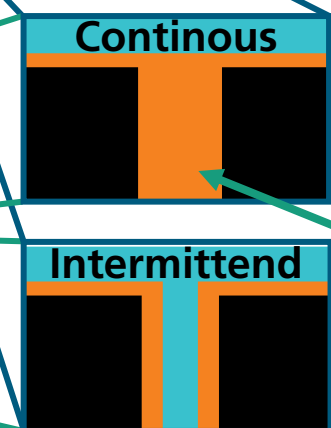
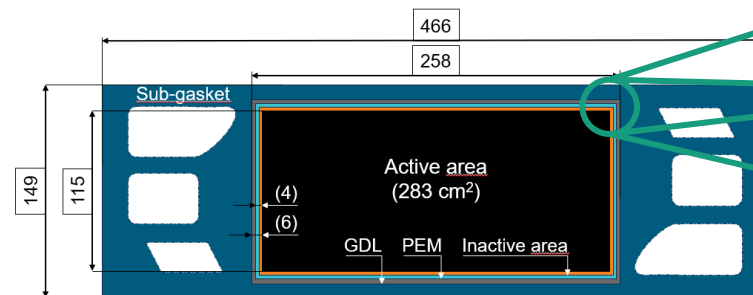
MEA_{7L} Fabrication

Performance Sensitivity

Pt-Loading [mg _{Pt} /cm ²]					Cathode	Anode
Coating Technology		RSP			Interm.	Conti.
			SDC _{int} RSP _{extra-tol.}		Interm.	Conti.
				SDC _{con}	Conti.	Conti.
Process Tolerances:	Coating - MD *	80 µm *	4,7 mm ^[1]	-	-	-
	Coating - CD *	80 µm *	3,6 mm ^[2]	3,6 mm ^[2]	-	-
	Transfer *				-	200 µm
	CCM cut *				100 µm	-
	Sub-Gasket Application *				200 µm	200 µm



➤ How do tolerances / inactive area influence the cost of the MEA_{7L}?

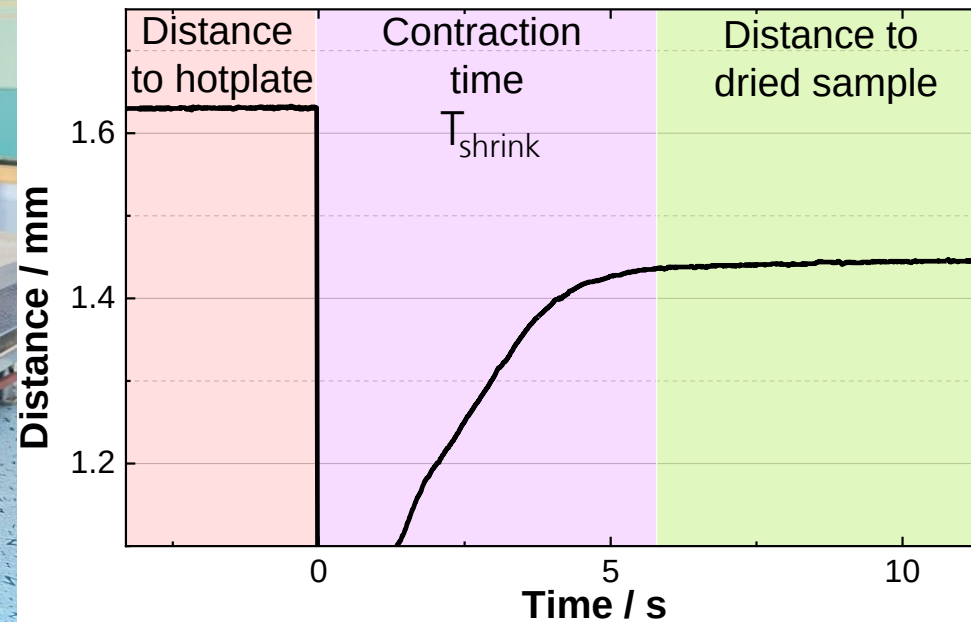


Inactive area

* Assumption

[1] Diehm et al. (2019): Edge Formation in High-Speed Intermittent Slot-Die Coating of Disruptively Stacked Thick Battery Electrodes. Energy Technol.;5:1900137.

[2] Spiegel et al. (2022): Investigation of edge formation during the coating process of Li-ion battery electrodes. J Coat Technol Res;19(1):121–30.



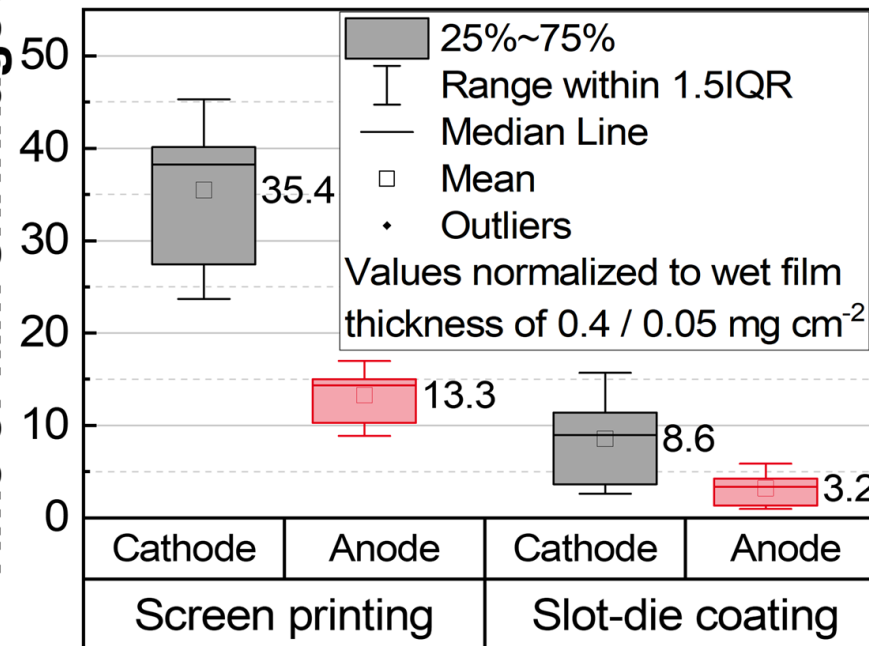
Minimum Dryer Length

- $L = L_{const} + v_{coat} * t_{dry} \quad [m]$
- t_{shrink} scaled by wet layer thickness of Cathode / Anode [1]

[1] Quarz et al. (2024): About drying phenomena of fuel cell and electrolyzer CCM inks: Selectivity of the evaporation of 1-propanol/water mixtures. Fuel Cells;24(2):108–21.[2] Jaiser et al. (2016): Investigation of film solidification and binder migration during drying of Li-Ion battery anodes. J. of Power Sources;318:210–9.



Time of film shrinkage / s



Minimum Dryer Length

- $L = L_{const} + v_{coat} * t_{dry} \quad [m]$
- t_{shrink} scaled by wet layer thickness of Cathode / Anode [1]
- t_{dry} determined by proportional scaling of t_{shrink} [2] & safety factor of 2 to assume min. convection dryer length

[1] Quarz et al. (2024): About drying phenomena of fuel cell and electrolyzer CCM inks: Selectivity of the evaporation of 1-propanol/water mixtures. Fuel Cells;24(2):108–21.

[2] Jaiser et al. (2016): Investigation of film solidification and binder migration during drying of Li-Ion battery anodes. J. of Power Sources;318:210–9.

Scenario Description

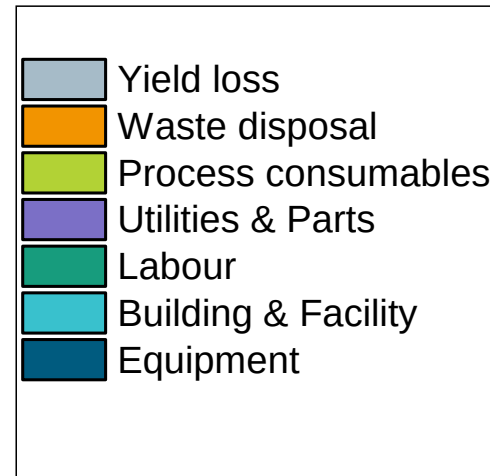
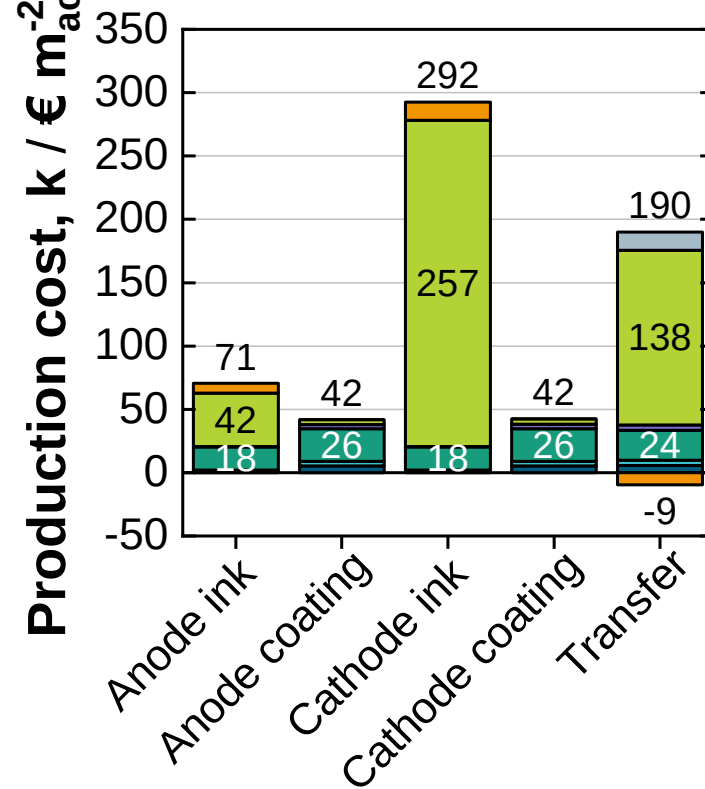
Consumable Cost Modeling

CCM Fabrication

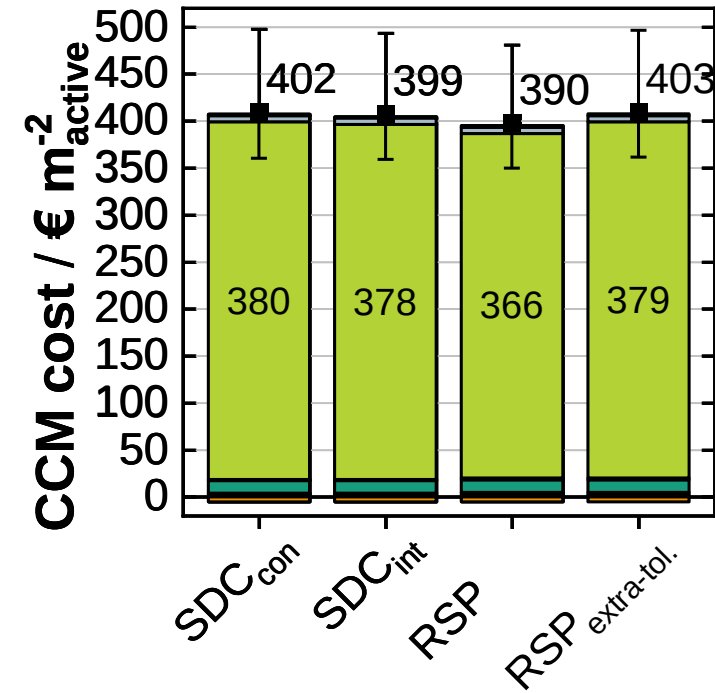
MEA_{7L} Fabrication

Performance Sensitivity

SDC_{int} - 1 m min⁻¹ - 1,250 m



Coating method variation



Scenario
Description

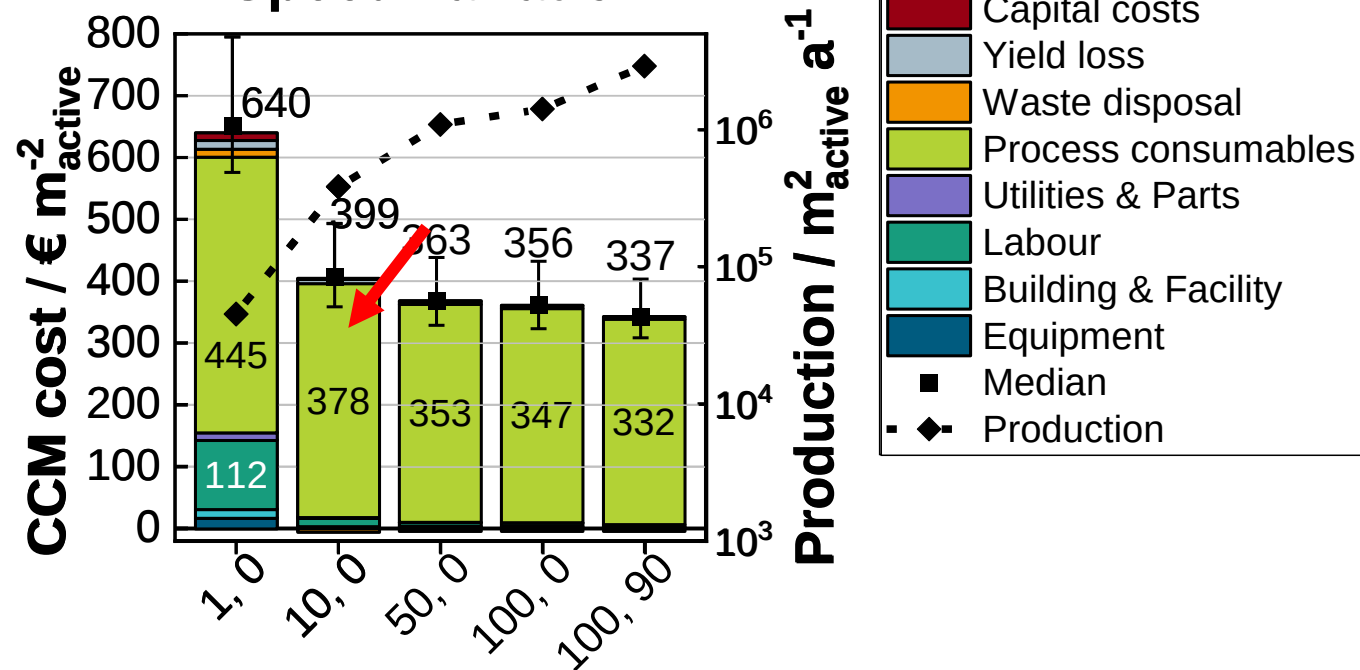
Consumable
Cost Modeling

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Fabrication

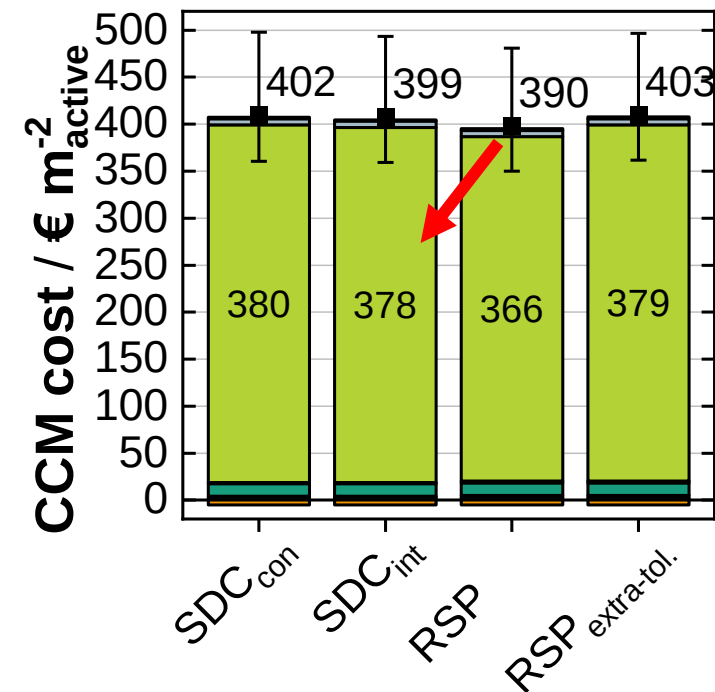
Performance
Sensitivity

Speed variation



Coating speed / m min⁻¹, Orientation / °

Coating method variation



Scenario
Description

Consumable
Cost Modeling

CCM Fabrication

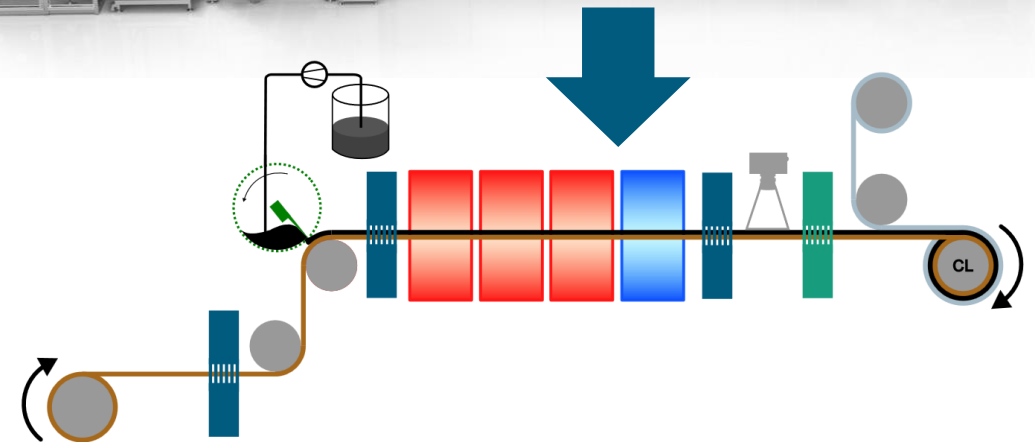
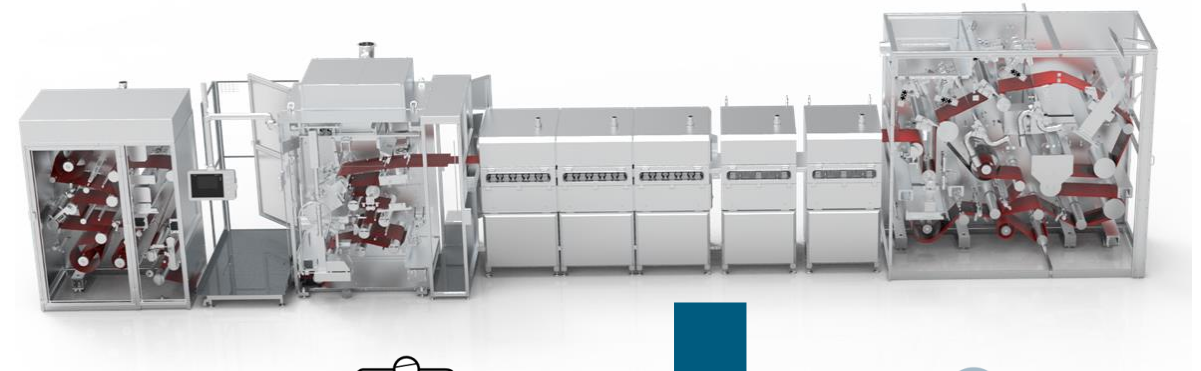
MEA_{7L}
Fabrication

Performance
Sensitivity

Conclusion

- **Coating methods** with given assumptions only show minor impact on cost -> performance to be considered
- Material based consumable modeling for flexible scenario variation
 - Throughput | Material composition

Machinery at Fraunhofer ISE

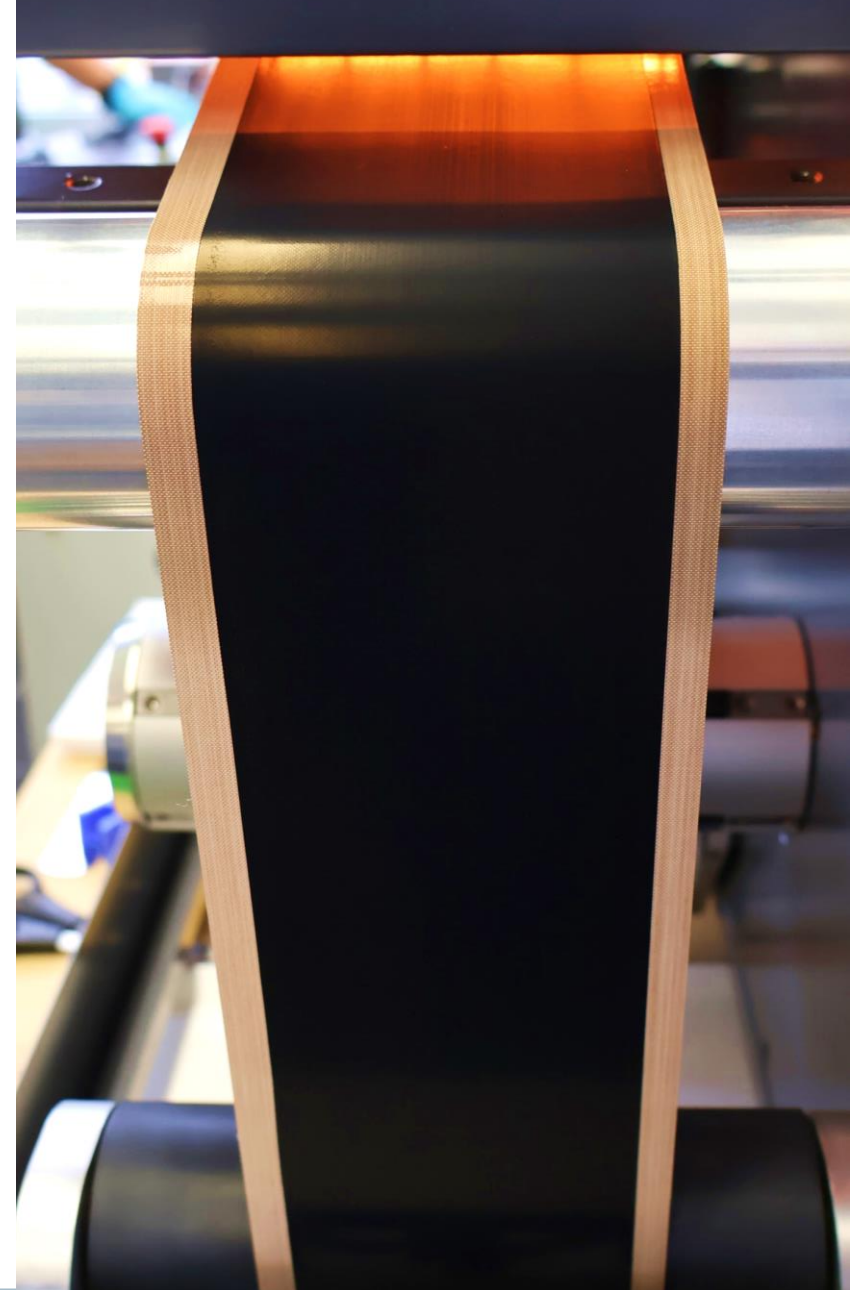


Comprehensive Cost Model

Impact of Coating Technologies on the Cost of PEMFC

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3. CCM Fabrication
4. MEA_{7L} Fabrication
5. Performance Sensitivity



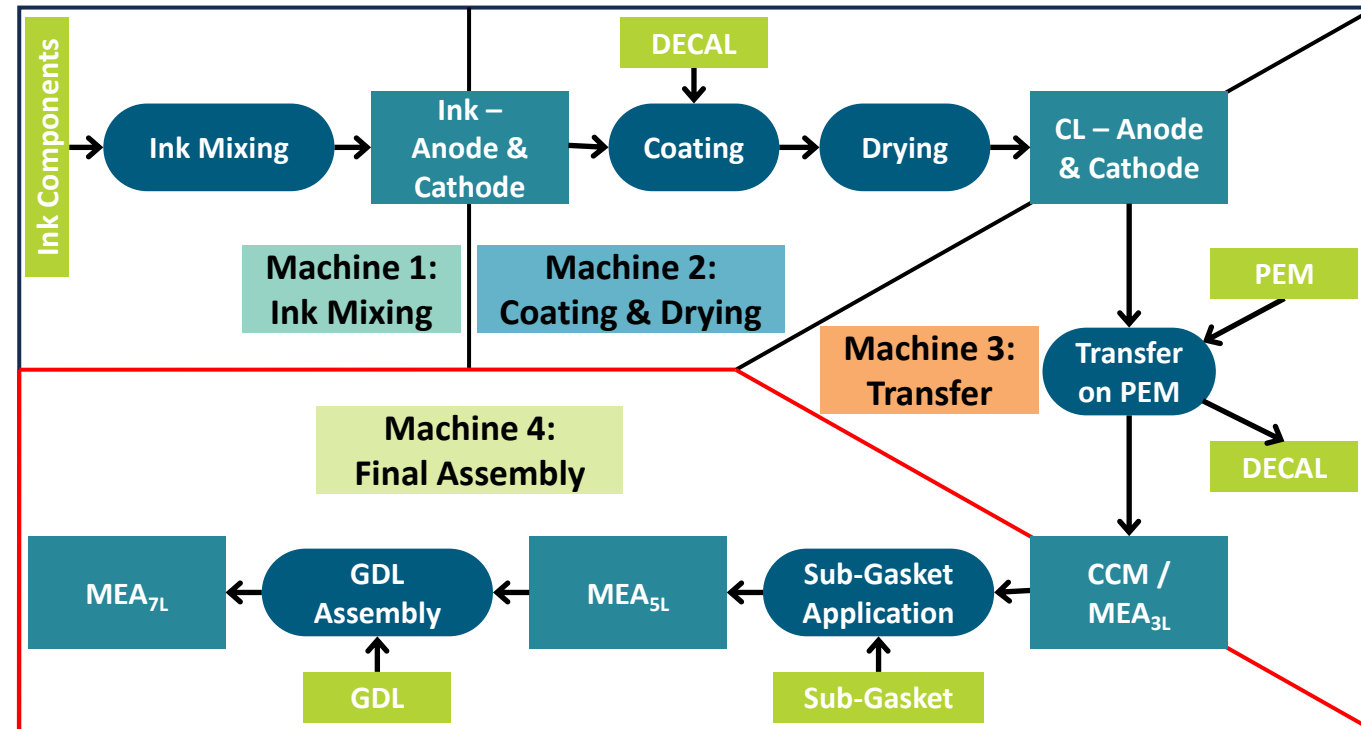
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CCM Fabrication

MEA_{7L} Fabrication

Performance Sensitivity



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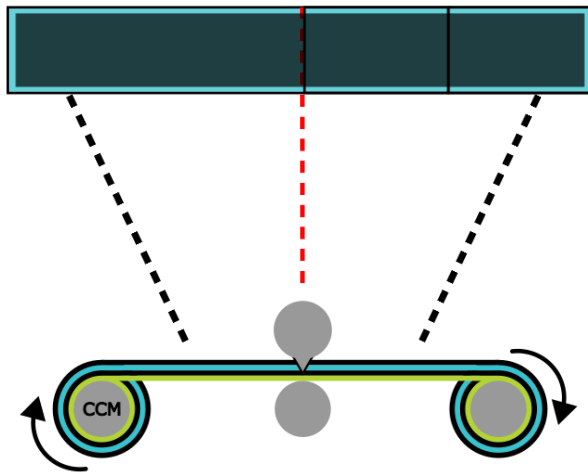
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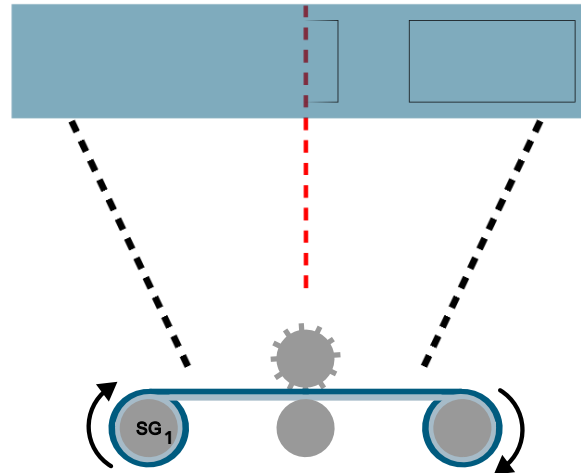
MEA_{7L}
Fabrication

Performance
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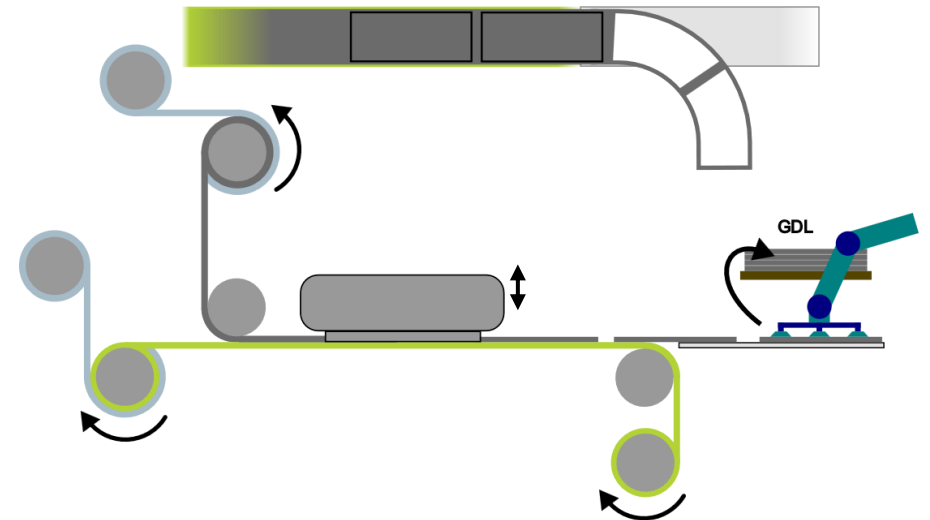
CCM Preparation

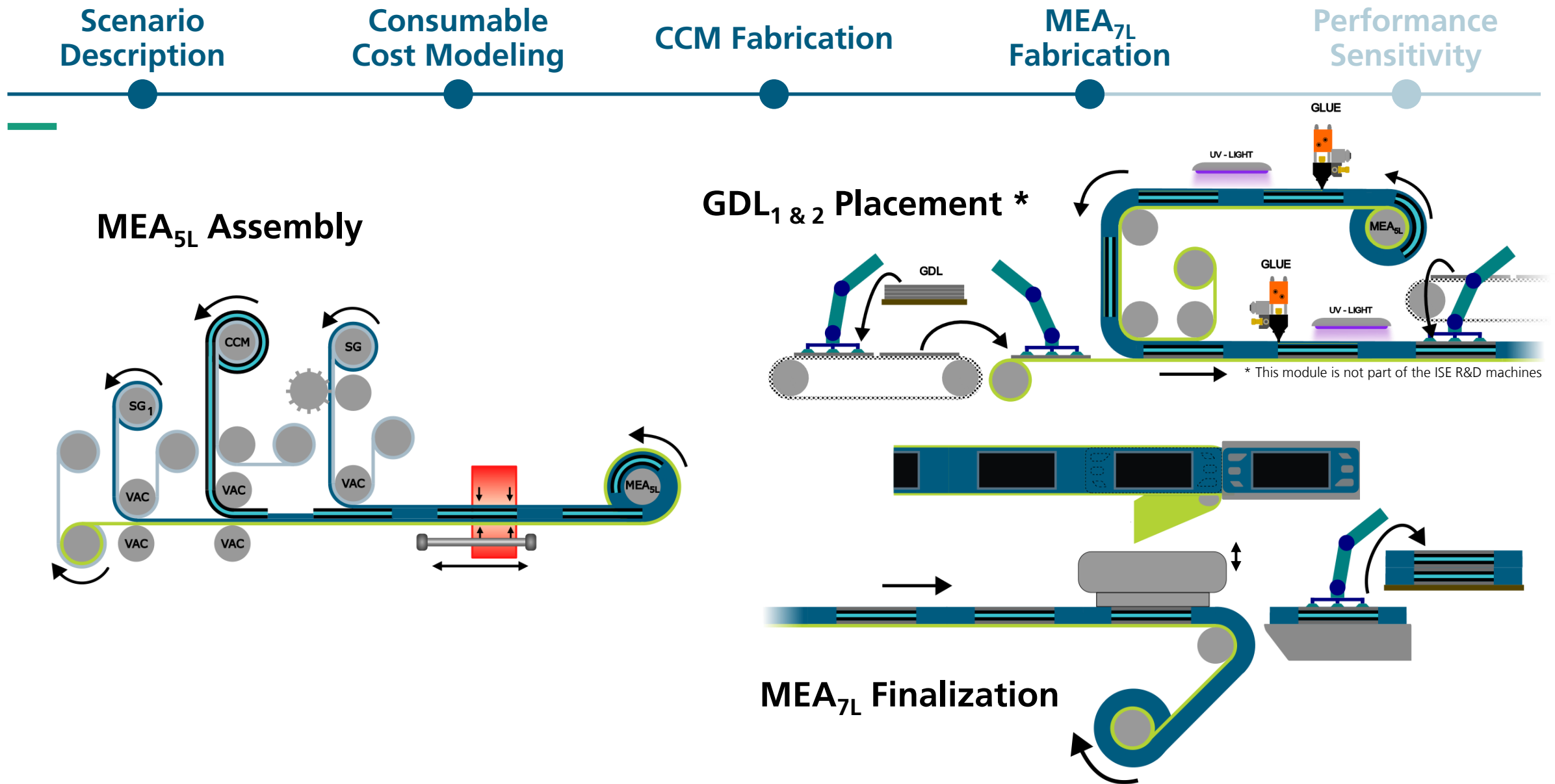


Sub-gasket Preparation



GDL Preparation





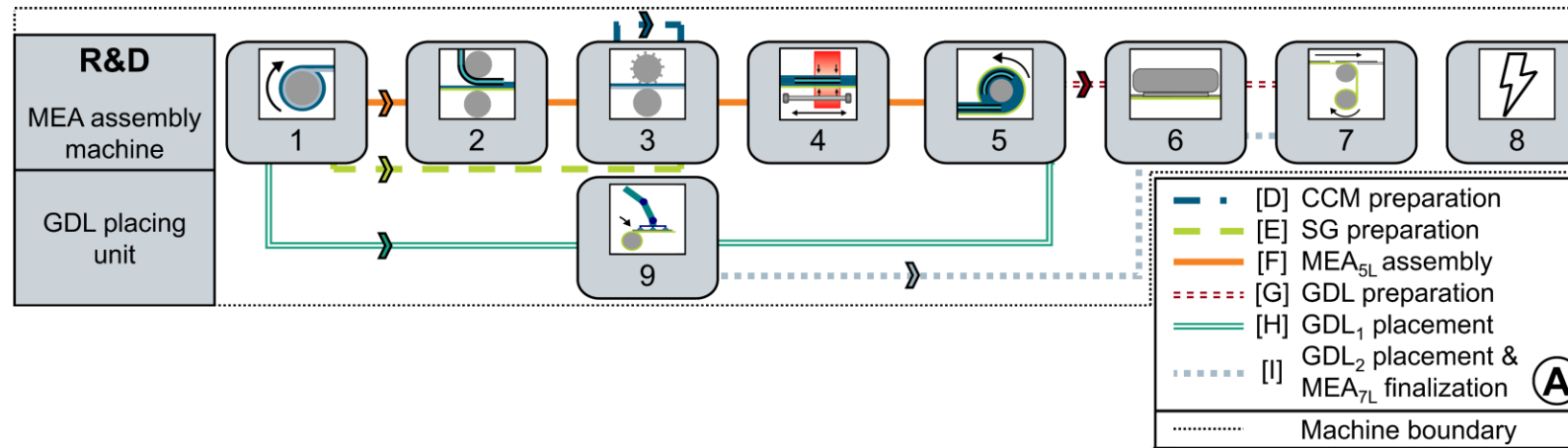
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Performance Sensitivity



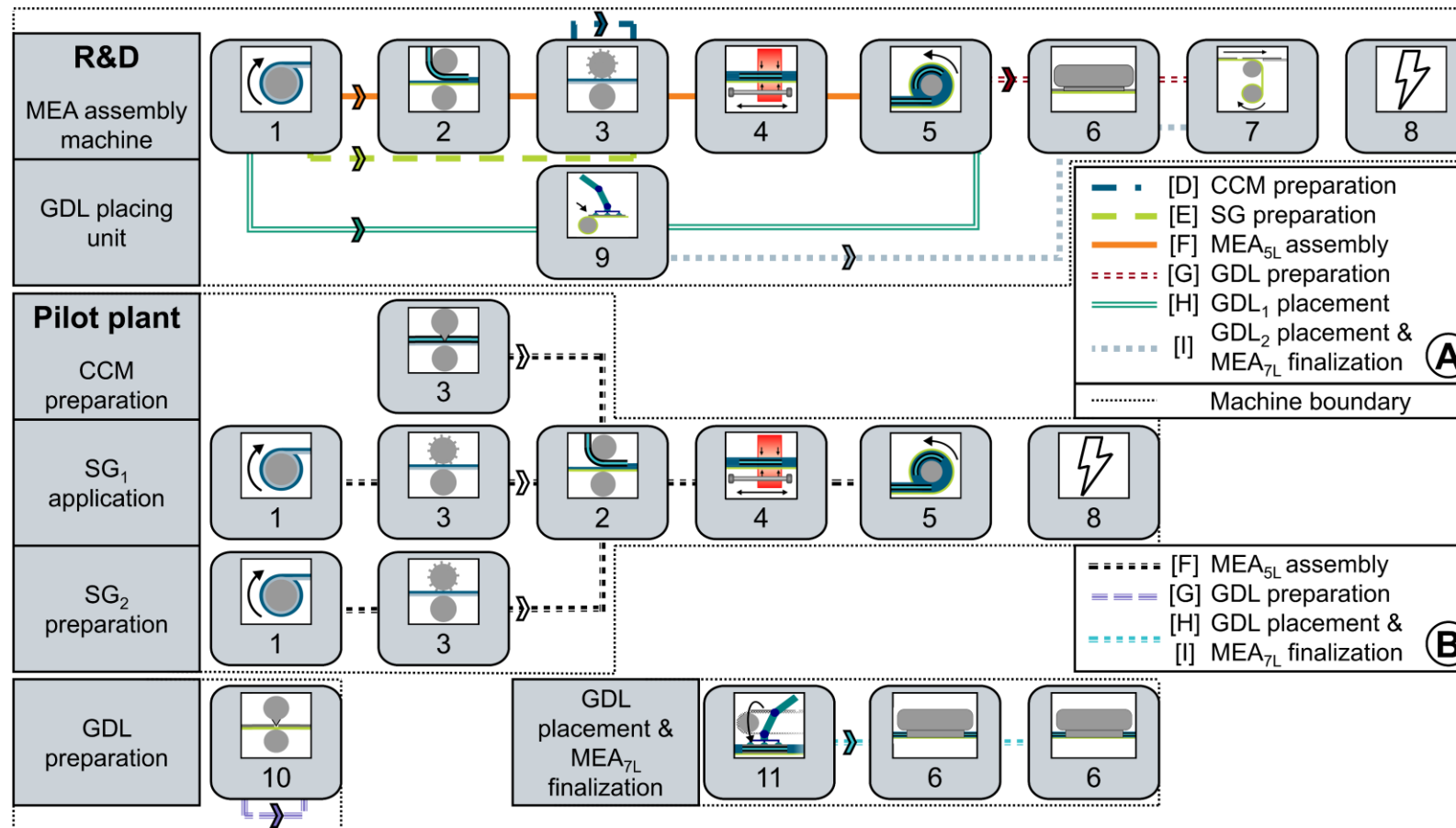
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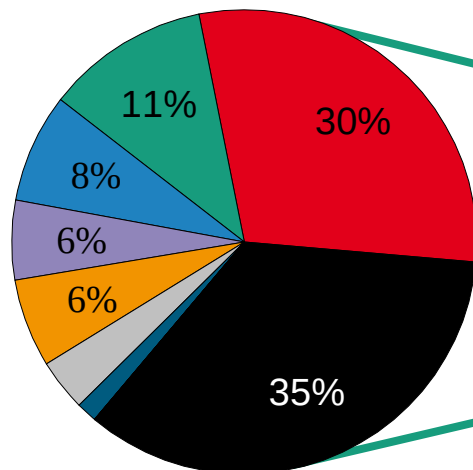
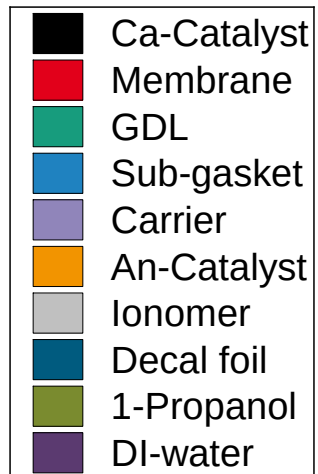
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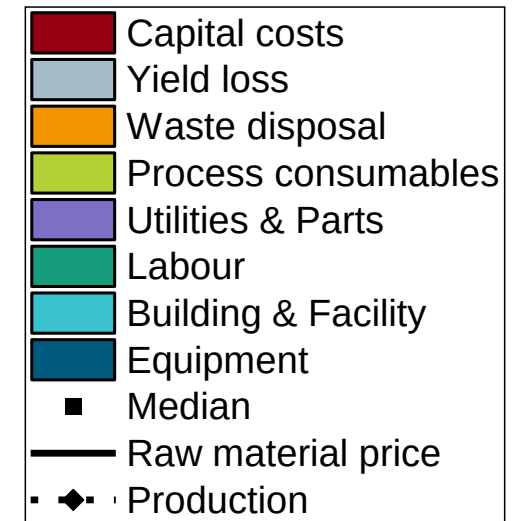
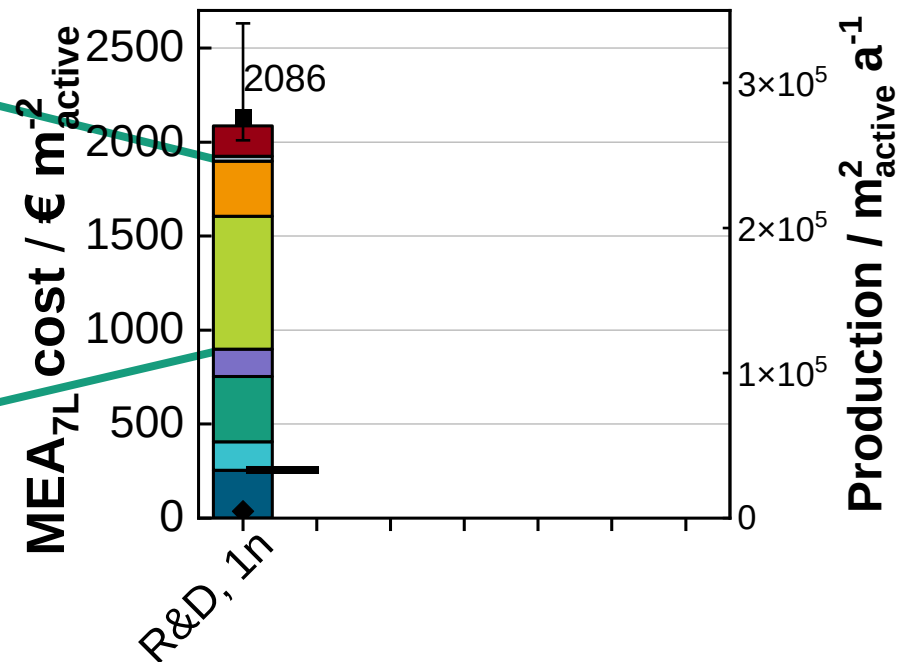
Performance
Sensitivity

1n = 250m batch length

Consumables



Scenario variation



Scenario
Description

Consumable
Cost Modeling

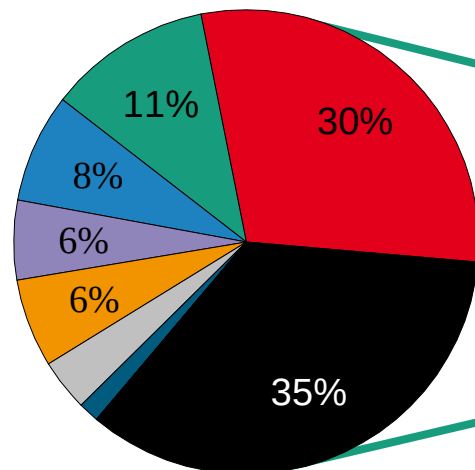
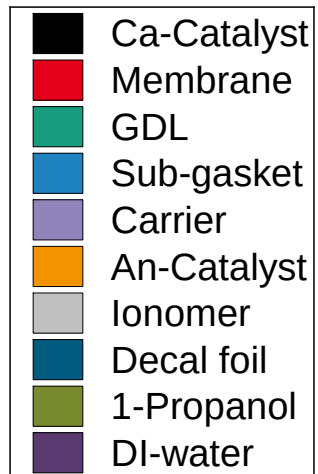
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MEA_{7L}
Fabrication

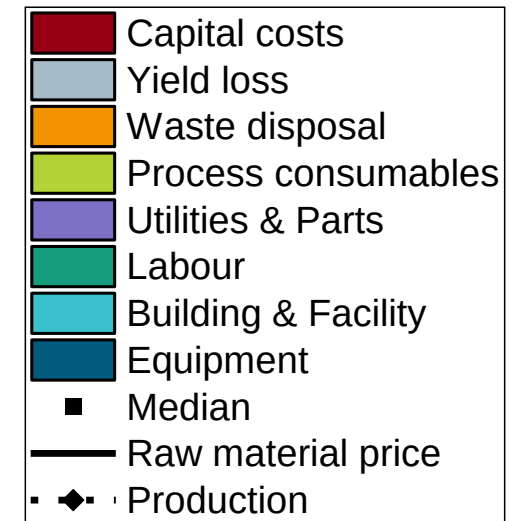
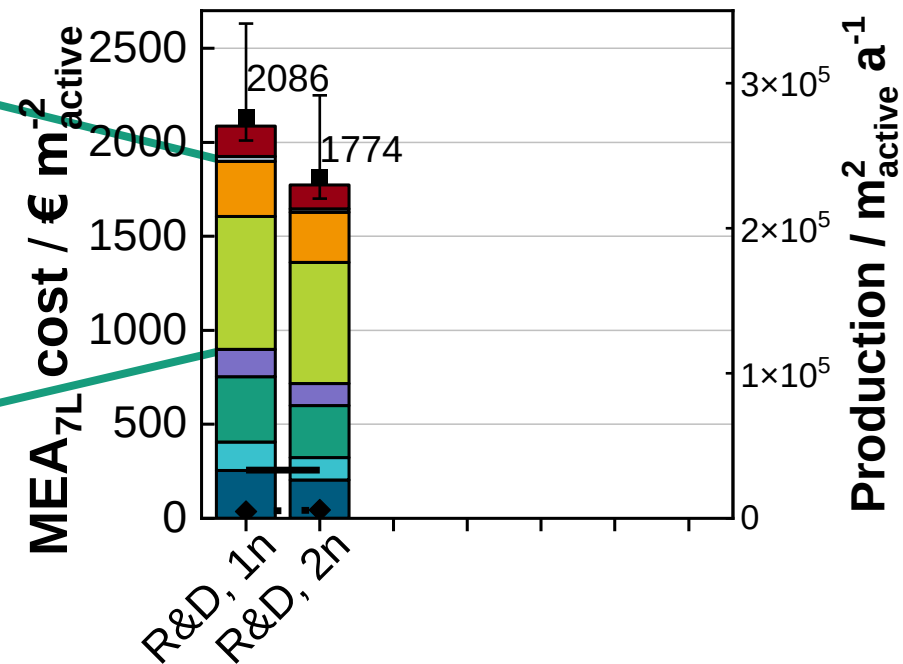
Performance
Sensitivity

1n = 250m batch length

Consumables



Scenario variation



Scenario
Description

Consumable
Cost Modeling

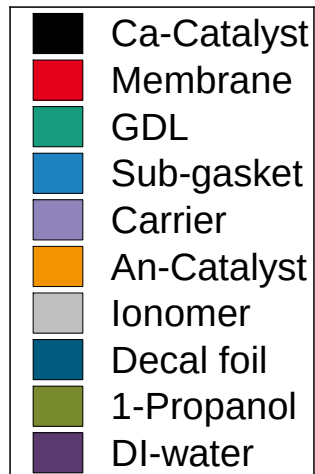
CCM Fabrication

MEA_{7L}
Fabrication

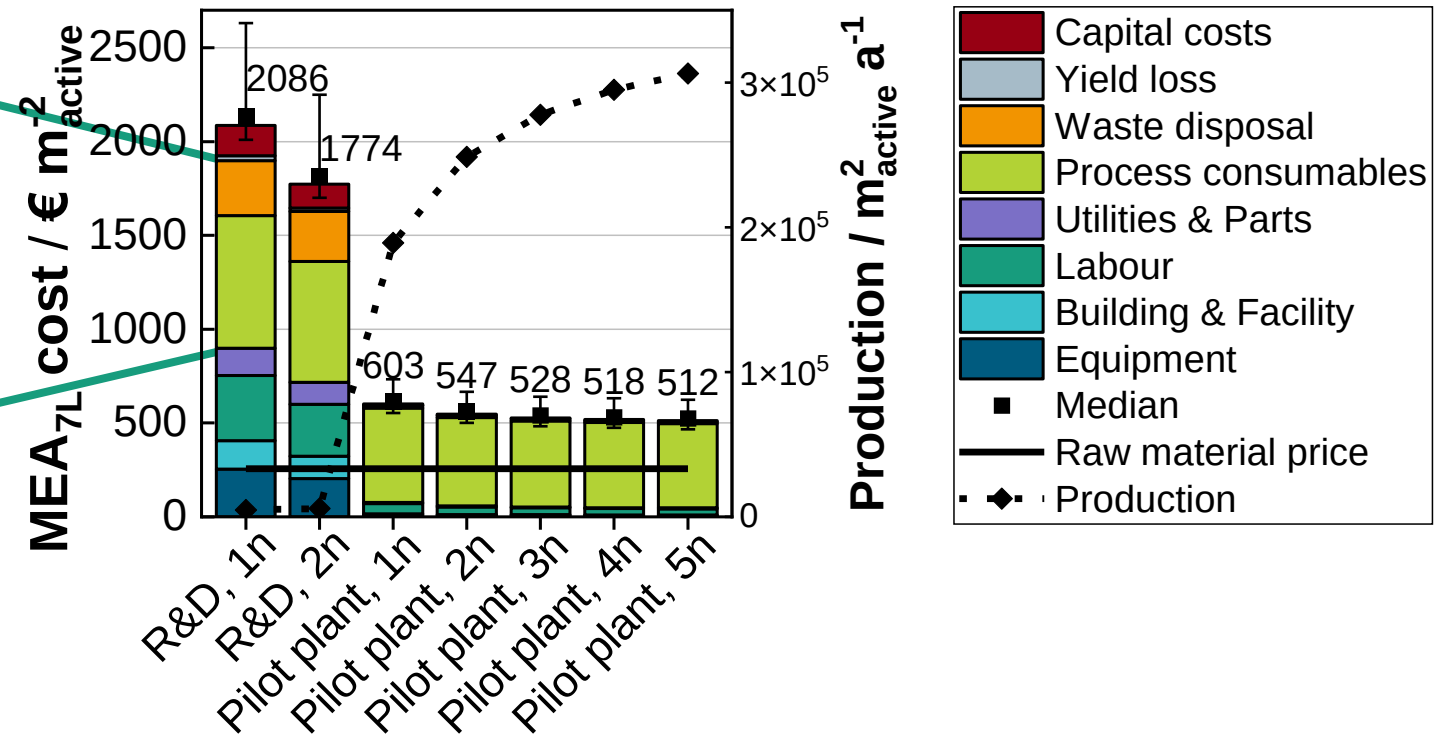
Performance
Sensitivity

1n = 250m batch length

Consumables



Scenario variation



Scenario Description

Consumable Cost Modeling

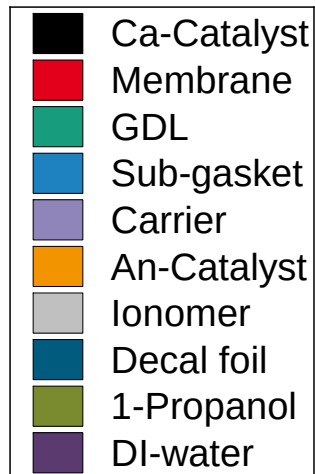
CCM Fabrication

MEA_{7L} Fabrication

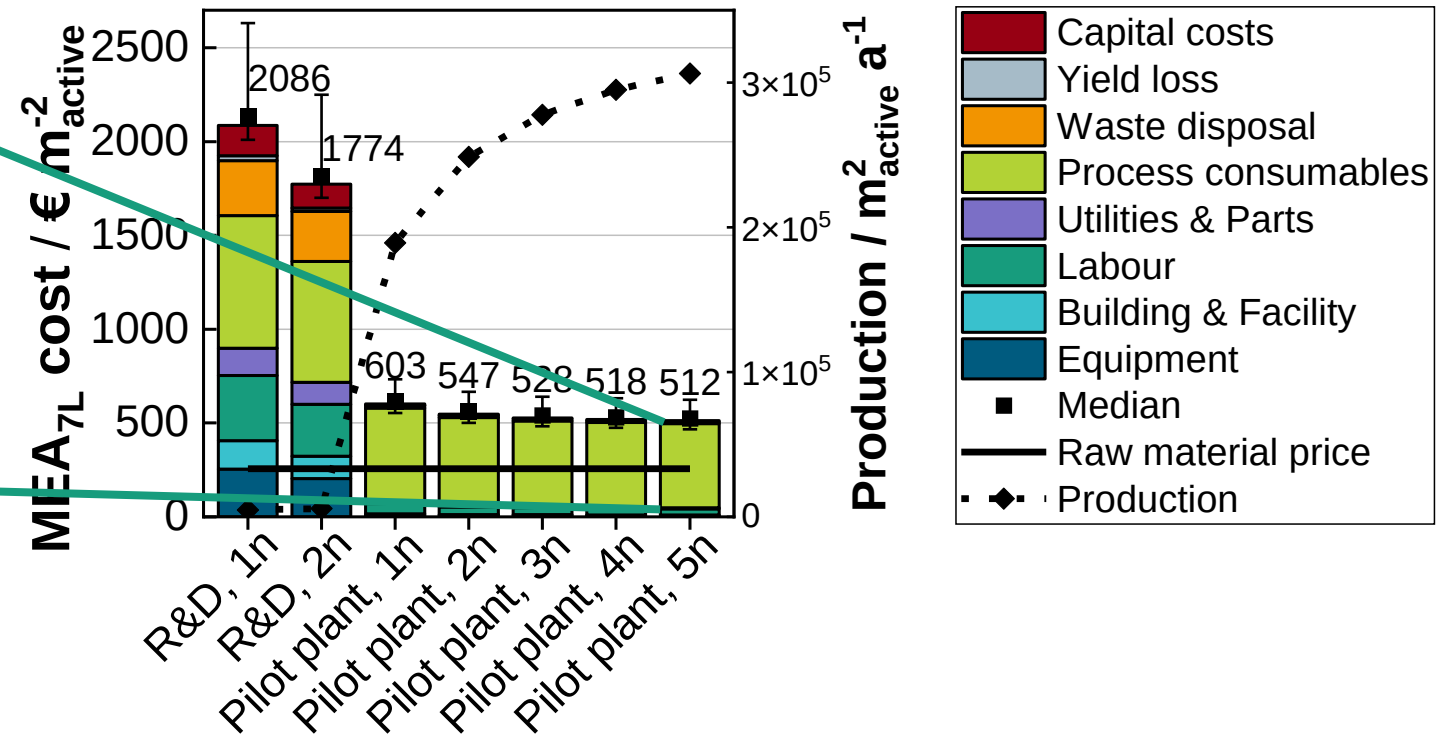
Performance Sensitivity

1n = 250m batch length

Consumables



Scenario variation





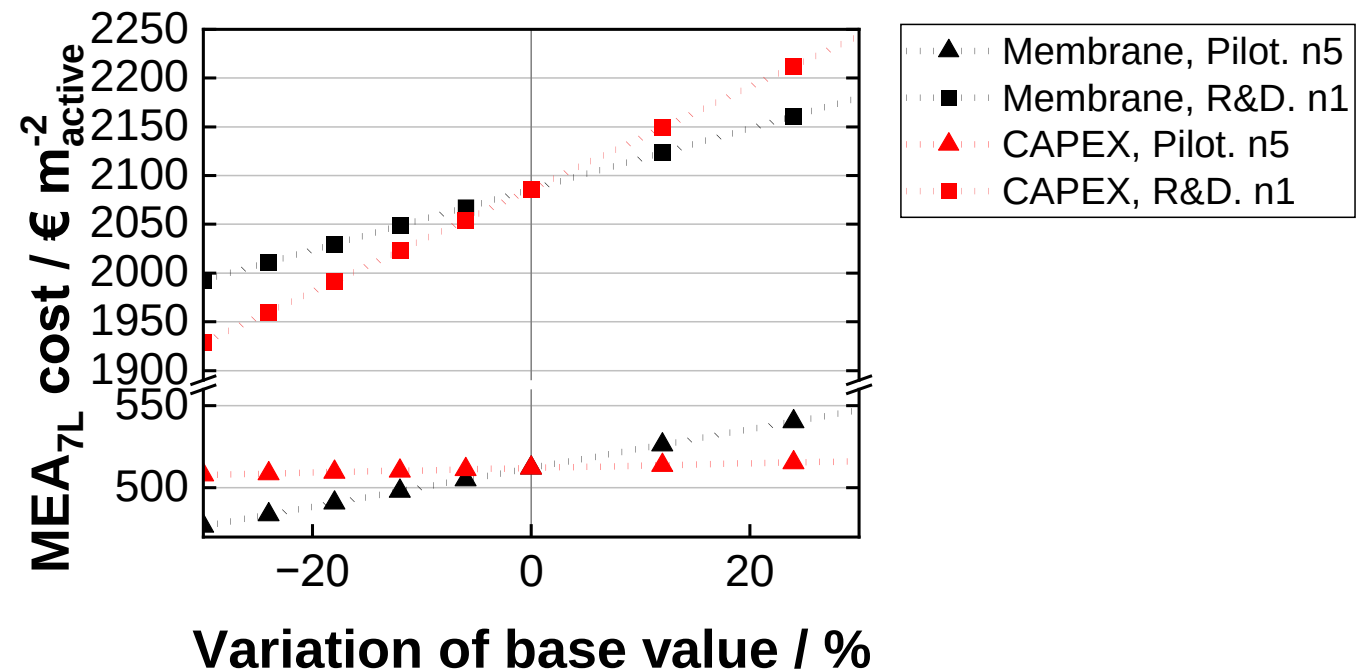
Influence on final MEA_{7L} cost

Research

- Capex > Membrane

Industry

- Membrane > Capex



Scenario
Description

Consumable
Cost Modeling

CCM Fabrication

MEA_{7L}
Fabrication

Performance
Sensitivity

Influence on final MEA_{7L} cost

Research

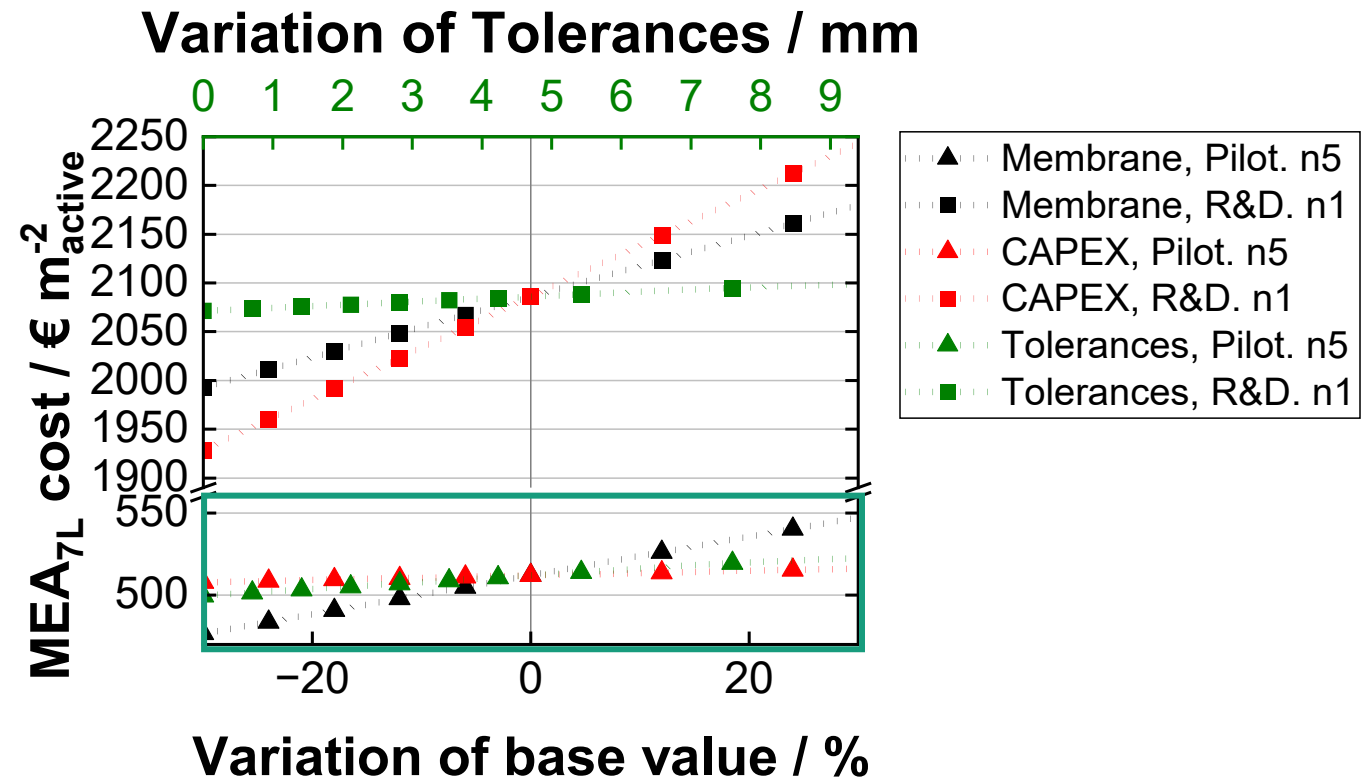
- Capex > Membrane
- Membrane > Tolerances

Industry

- Membrane > Capex
- Tolerances > Capex

Base Value Coating Tolerances:

- MD: 4.7 mm





Influence on final MEA_{7L} cost

Research

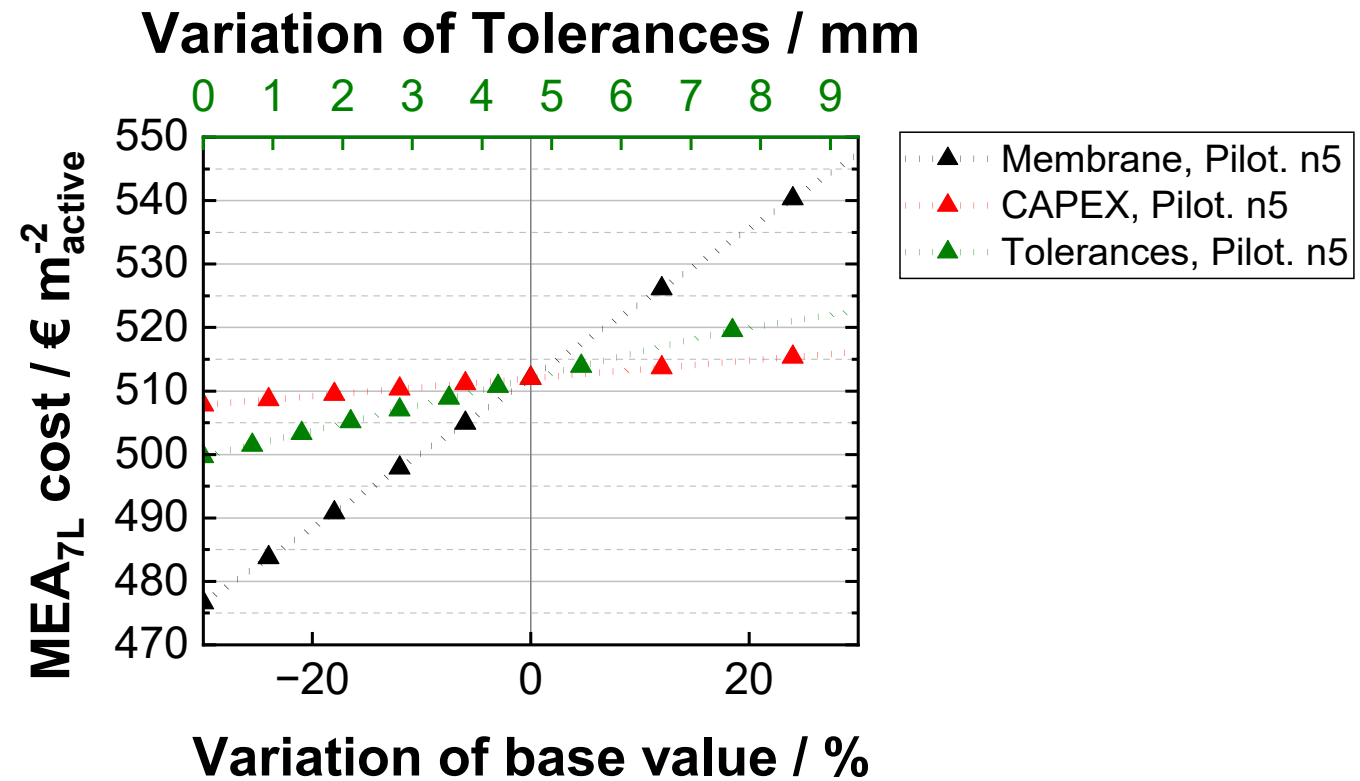
- Capex > Membrane
- Membrane > Tolerances

Industry

- Membrane > Capex
- Tolerances > Capex

Base Value Coating Tolerances:

- MD: 4.7 mm



Scenario
Description

Consumable
Cost Modeling

CCM Fabrication

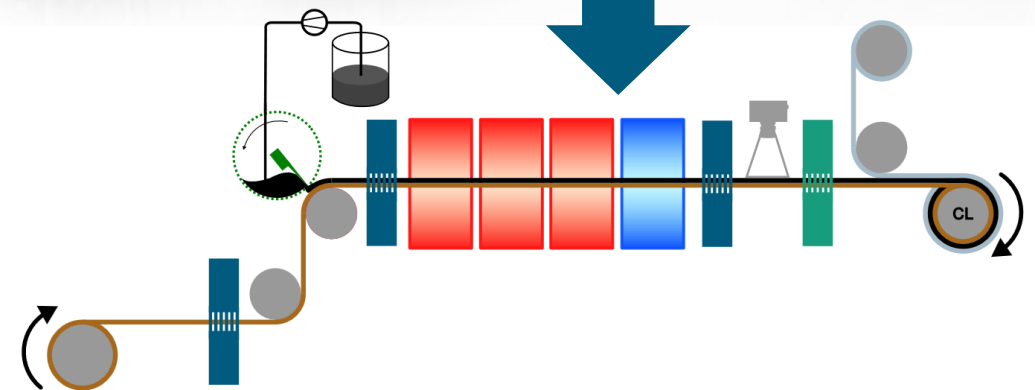
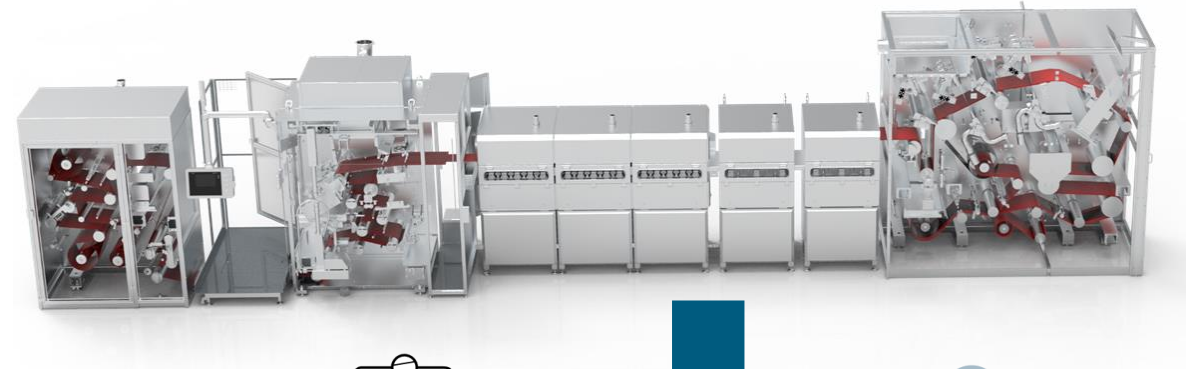
MEA_{7L}
Fabrication

Performance
Sensitivity

Conclusion

- **CCM -> MEA processes** add significant complexity to the manufacturing process
 - **Tighter tolerances** become more important at higher MEA annual volumes
 - **Membrane** as crucial cost next to the catalyst
- Coating methods with given assumptions only show minor impact on cost -> performance to be considered
- Material based consumable modeling for flexible scenario variation
 - Throughput | Material composition

Machinery at Fraunhofer ISE

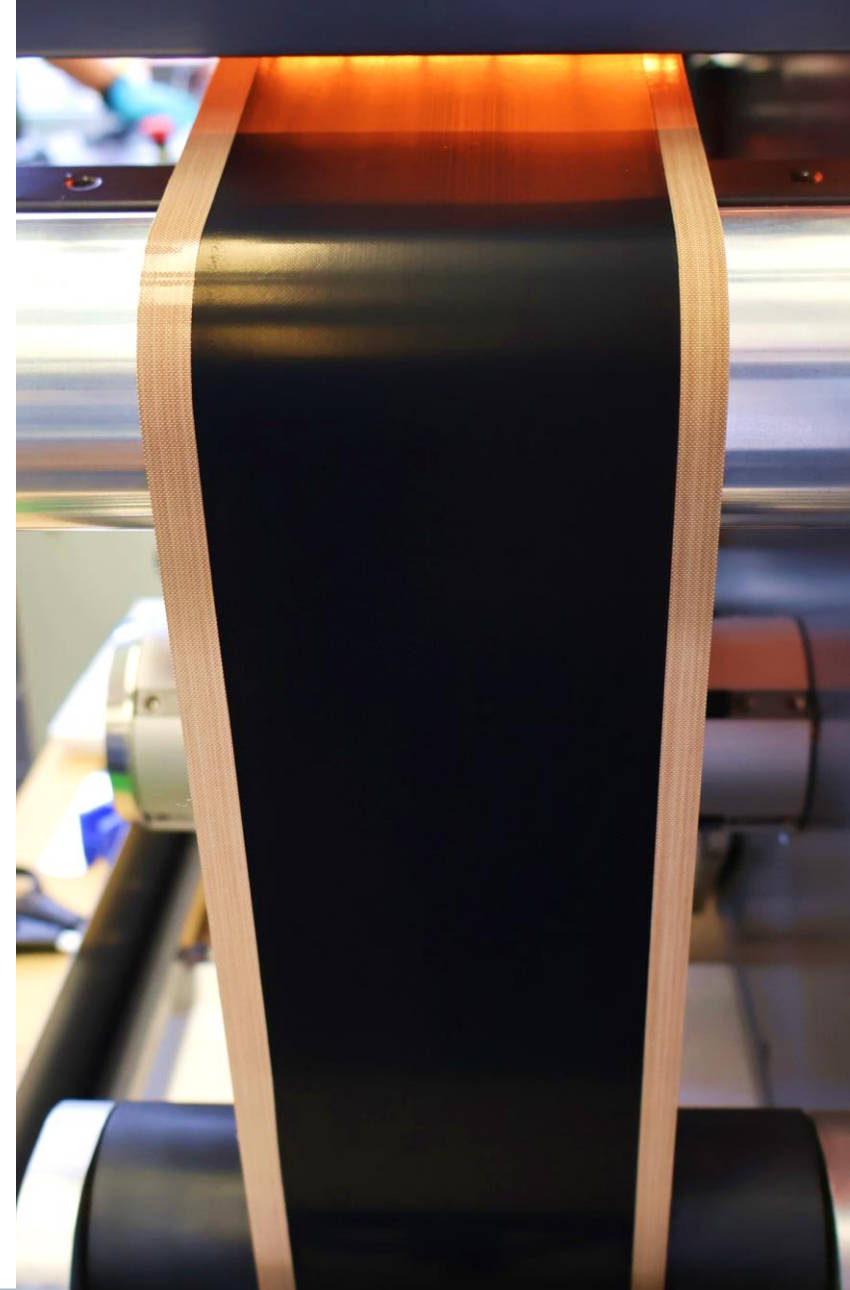


Comprehensive Cost Model

Impact of Coating Technologies on the Cost of PEMFC

Agenda

1. Scenario Description
2. Consumable Cost Modeling
3. CCM Fabrication
4. MEA_{7L} Fabrication
5. Performance Sensitivity



Scenario
Description

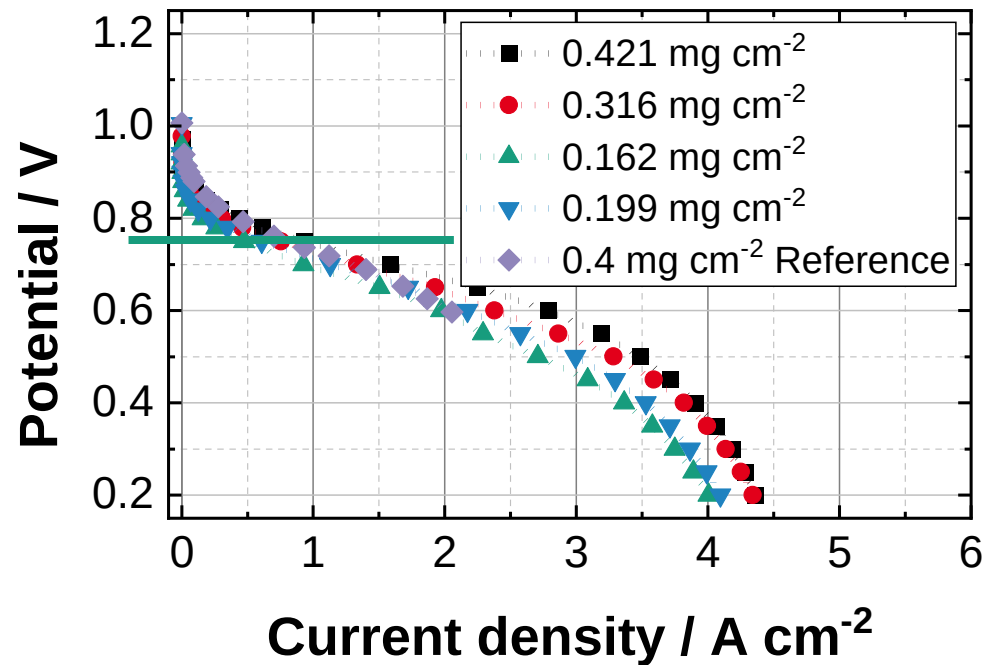
Consumable
Cost Modeling

CCM Fabrication

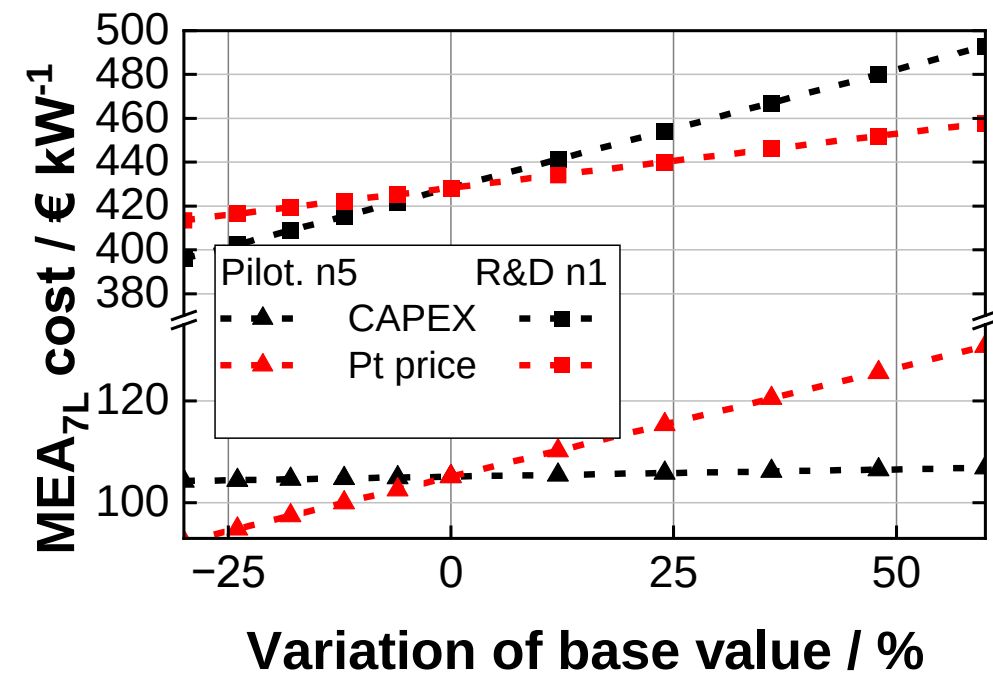
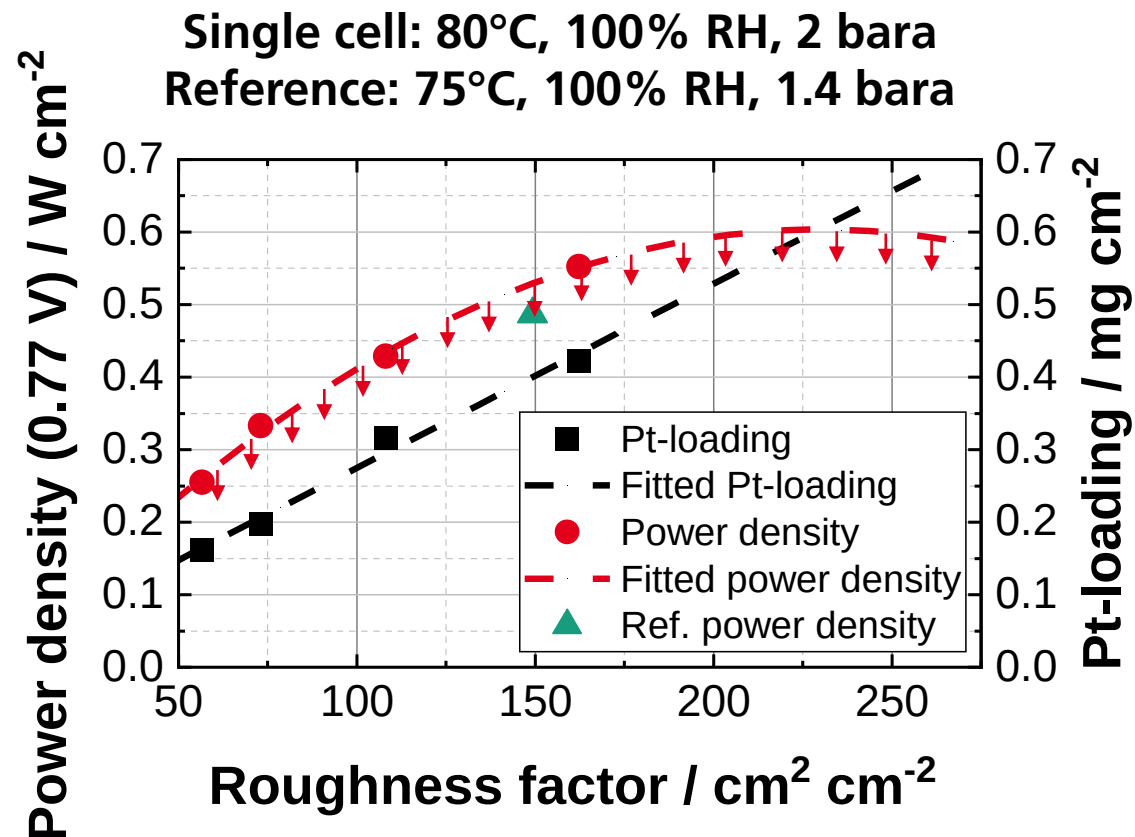
MEA_{7L}
Fabrication

Performance
Sensitivity

Single cell: 80°C, 100% RH, 2 bara
Reference: 75°C, 100% RH, 1.4 bara



[Reference] Ney et al. (2024): From Catalyst Ink to PEM Fuel Cell Stack: First Full-Size Screen Printed Catalyst Layers Tested within a Generic Stack. ECS Trans.;114(5):315–23.



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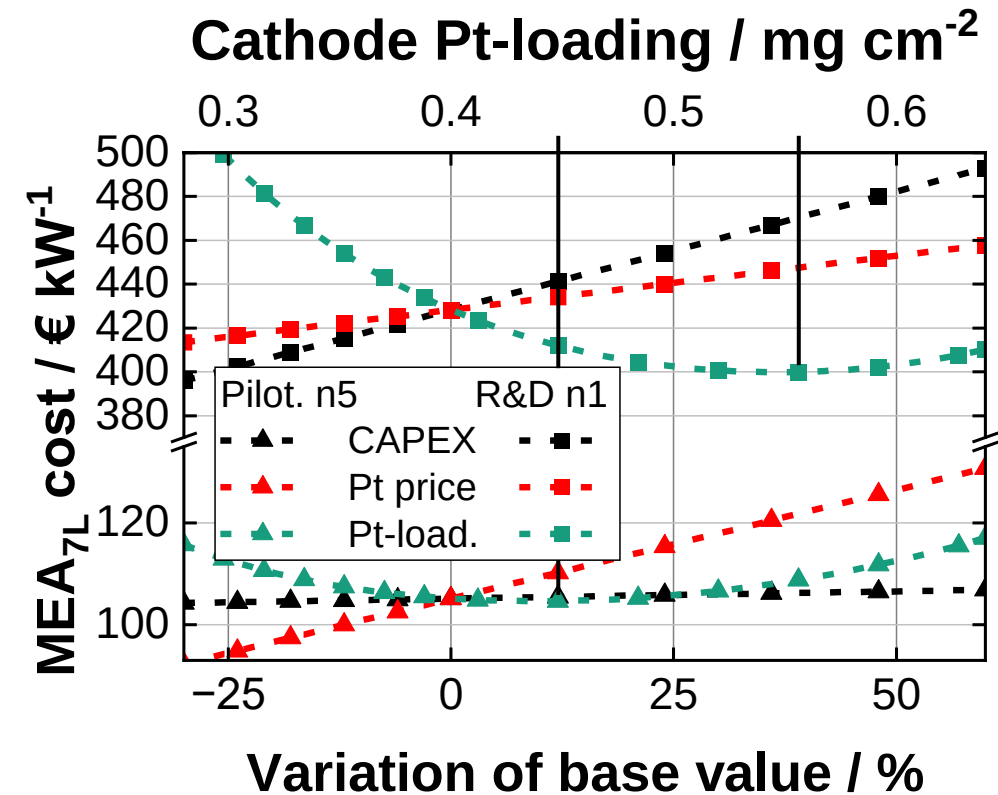
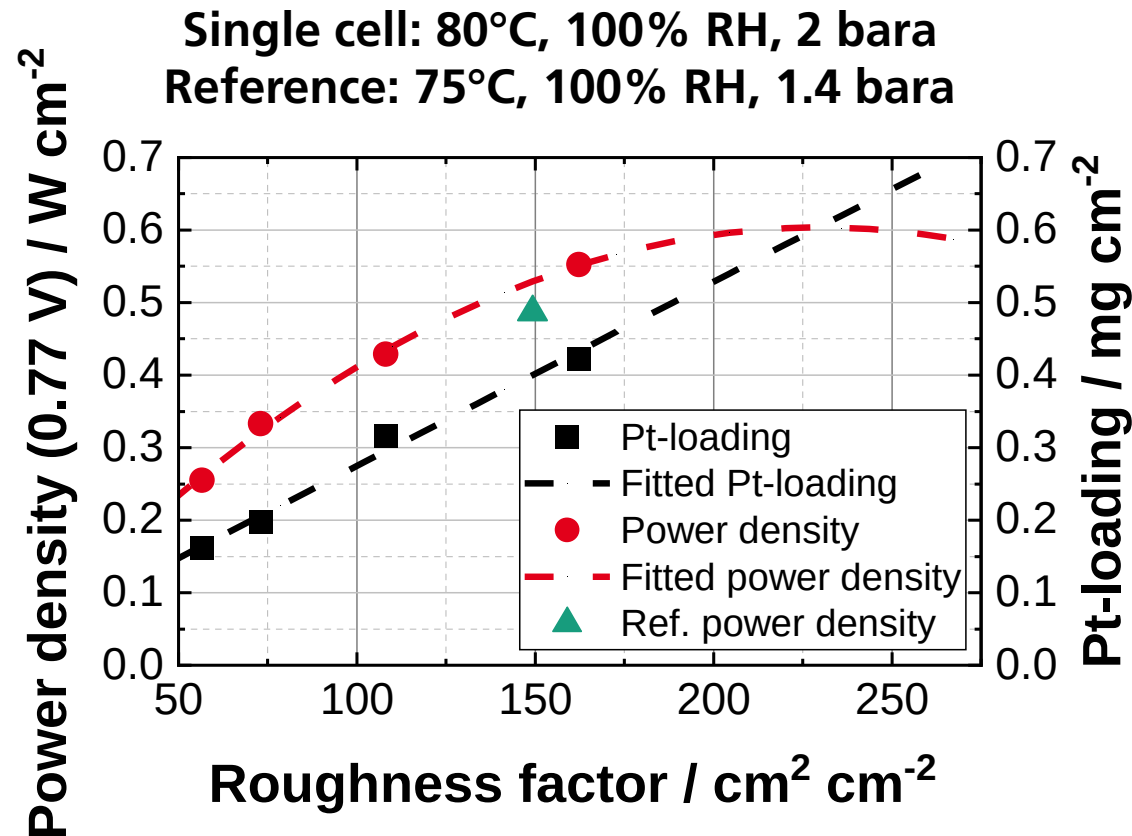
Scenario Description

Consumable Cost Modeling

CCM Fabrication

MEA_{7L} Fabrication

Performance Sensitivity



[Reference] Ney et al. (2024): From Catalyst Ink to PEM Fuel Cell Stack: First Full-Size Screen Printed Catalyst Layers Tested within a Generic Stack. ECS Trans.;114(5):315–23.

Scenario
Description

Consumable
Cost Modeling

CCM Fabrication

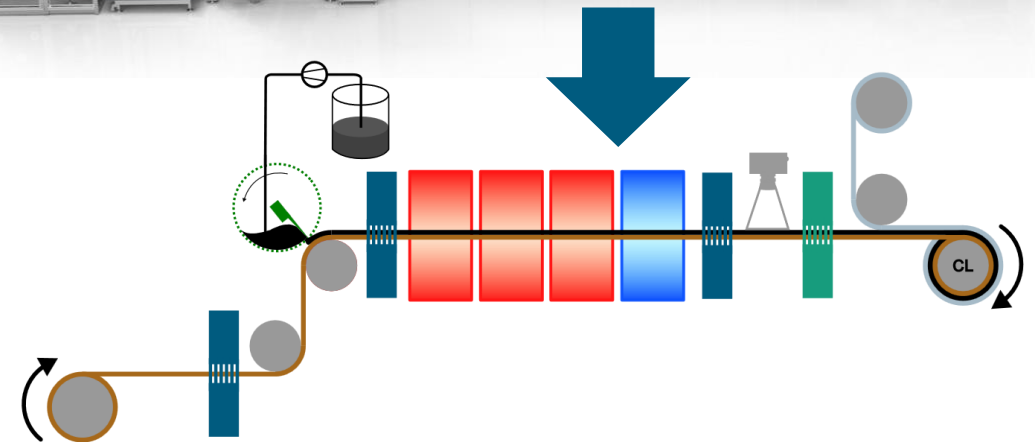
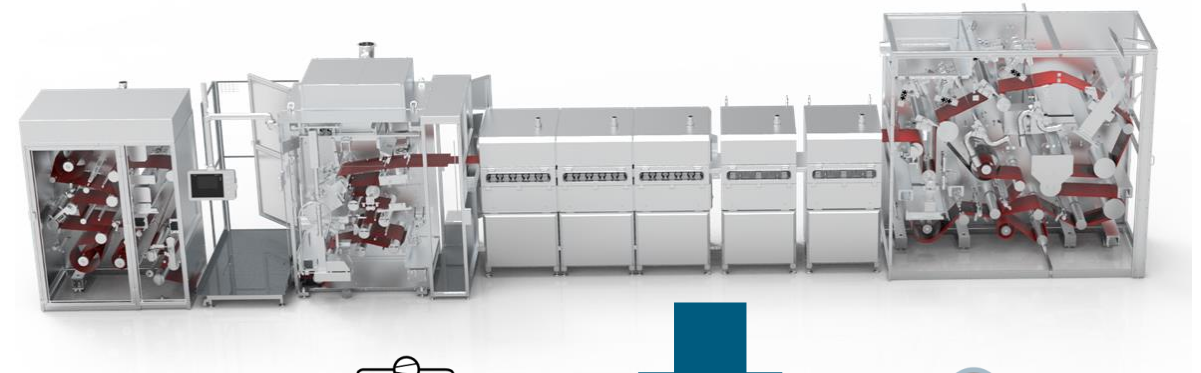
MEA_{7L}
Fabrication

Performance
Sensitivity

Conclusion

- Methodology for **cost-per-kW optimal Pt-loadings** for a given material selection
- **CCM -> MEA processes** add significant complexity to the manufacturing process
 - **Tighter tolerances** become more important at higher MEA annual volumes
 - **Membrane** as crucial cost next to the catalyst
- **Coating methods** with given assumptions only show minor impact on cost -> performance to be considered
- **Material based consumable modeling** for flexible scenario variation
 - Throughput | Material composition

Machinery at Fraunhofer ISE



Comprehensive Cost Model

RESEARCH ARTICLE OPEN ACCESS

Techno-Economic Assessment of Manufacturing Membrane Electrode Assemblies for PEM Fuel Cells: Focus on Coating Technologies

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Keywords: MEA production | PEM fuel cell | PL loading | rotary screen printing | slot-die coating | techno-economic assessment

ABSTRACT

High manufacturing costs of proton exchange membrane (PEM) fuel cells remain a significant obstacle to their widespread adoption in transportation applications. To address this, roll-to-roll (R2R) processes are proposed to increase production throughput and reduce membrane electrode assembly (MEA) costs. Among R2R-compatible coating processes, slot-die coating (SDC) represents the state-of-the-art technology, while rotary screen printing (RSP) offers advantages in structured and intermittent printing, providing additional design freedom for catalyst layers (CL). This study examines the cost implications of both coating processes for a specific set of R2R machines to be implemented at Fraunhofer ISE. Technical boundary conditions and operational limitations are evaluated and integrated into a comprehensive continuous process cost of ownership model capturing expenses throughout the production chain, from catalyst ink raw materials to the final seven-layer MEA. A methodology is presented for determining consumable costs at various purchasing volumes, combining literature values with supplier quotations. By integrating performance data from experimentally produced MEAs with the cost model, an approach is developed to determine optimum platinum (Pt) loadings for cost per kW for given materials. The identified optimal Pt loadings of $0.44\text{--}0.54\text{ mg Pt cm}^{-2}$ demonstrate that the cell performance is crucial for further cost reductions of fuel cells.

1 | Introduction

It is widely acknowledged that increasing the manufacturing volume reduces the cost of a final product [1]. However, the critical question centers on identifying precisely where these cost savings emerge within the manufacturing process chain and what insights can be derived to further optimize the product design. For proton exchange membrane fuel cells (PEMFCs), this understanding is particularly valuable since the membrane electrode assembly (MEA) remains one of the dominant cost drivers in a complete stack [2].

emission technology for decarbonizing the transport sector, which accounts for approximately 20% of global CO₂ emissions [3, 4]. Special focus is placed on PEMFCs for heavy-duty vehicles, as in Europe they contribute a disproportionate 23% of transport emissions while representing only 2% of all vehicles [5, 6].

Despite achieving technical maturity at laboratory scale, the large-scale market penetration of PEMFCs continues to face economic and production-related challenges [7, 8]. The MEA represents the core component and requires costly as well as specialized materials like platinum-based inks and perfluorosulfonic acid membranes. These inks are processed into catalyst



Thank You for Your Attention!

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H2GO

Project Management:

Projektträger Jülich
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