Materials for electrochemical energy conversion and storage

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3rd Minisymposium on Materials, Characterization and Modelling
under the auspices of the Rector of AGH, prof. Jerzy Lis

31 January 2025, AGH University of Krakow

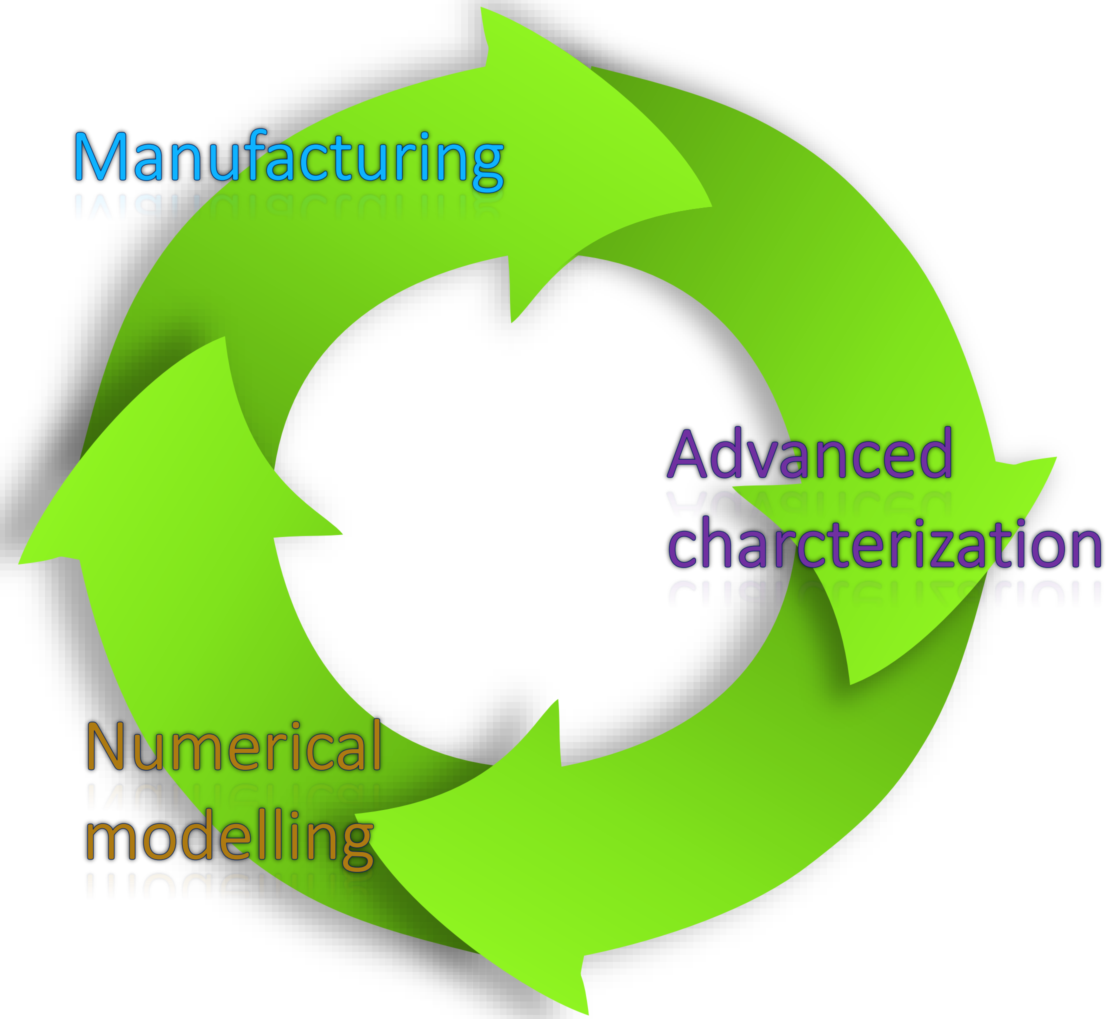
Outline

CONVERSION

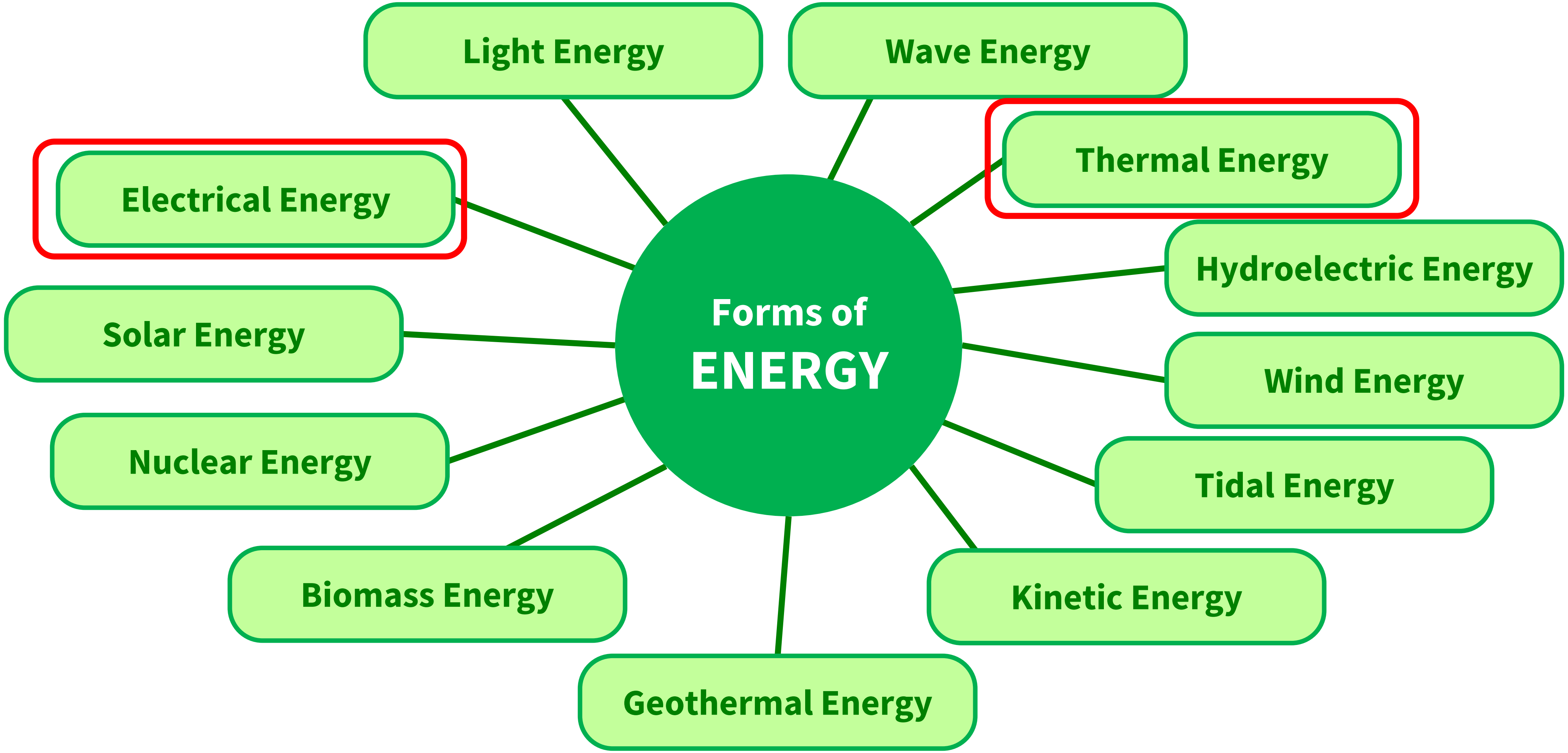
1. Introduction to technologies for Energy „Production" Conversion
2. Energy conversion through electrochemical processes – **Fuel cells**
3. Hydrogen -> **Syntetic fuels** -> fuel cells

STORAGE

1. Introduction to Energy Storage technologies
2. **Hydrogen vs Batteries**
3. **Supercapacitors**
4. **Chemical storage of hydrogen**



Forms of Energy



Basing on: https://www.geeksforgeeks.org/energy-conversion/

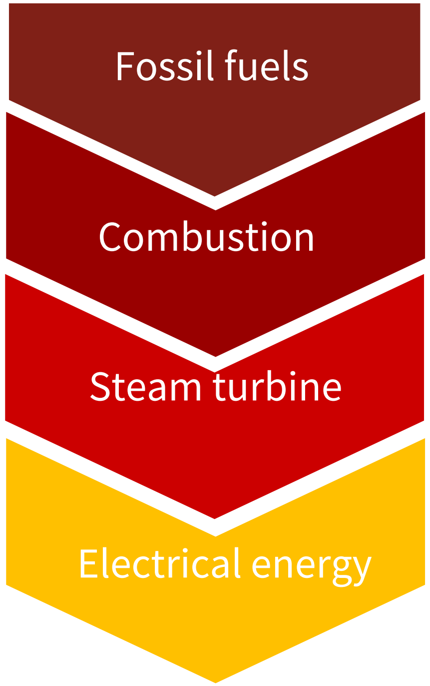
„Production” of energy

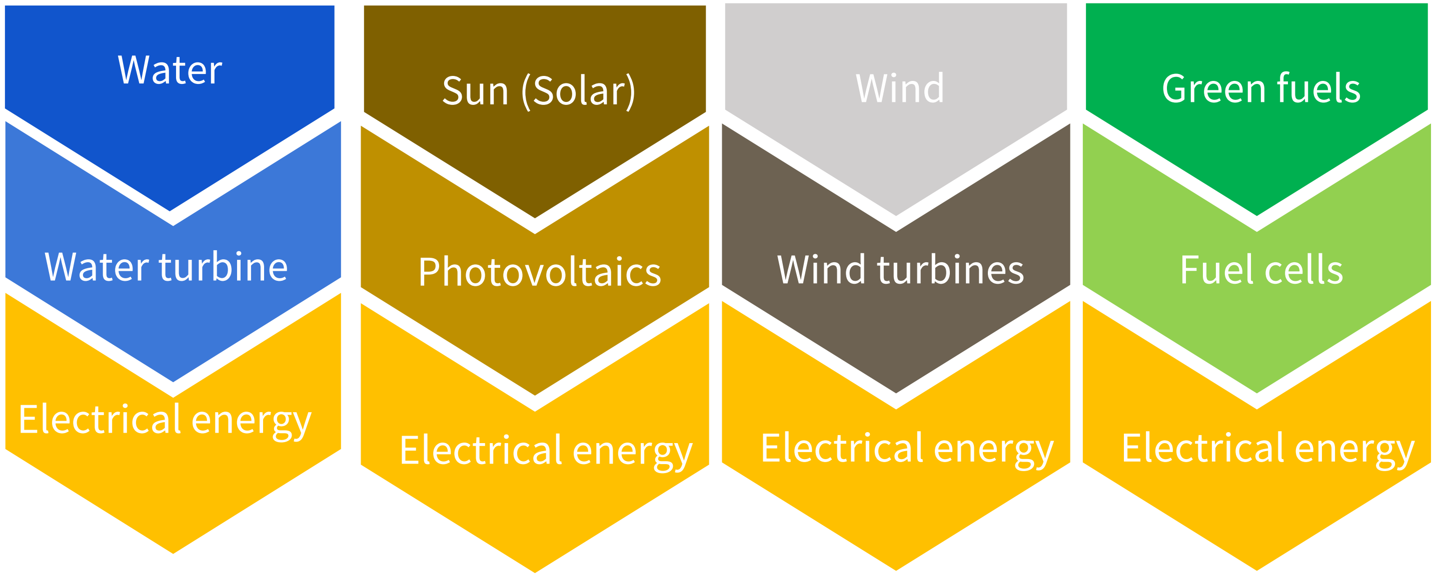
Conventional

The production of electricity and heat through the **combustion of fuels**, which include, for example, hard coal, lignite, oil, gas, biogases, biomass (plant and animal), peat

Non-conventional

Obtaining electricity and heat from alternative sources, including: flowing waters, geothermal waters, wind, sun, sea tides, green fuels, nuclear reactions, and ambient heat.





Energy distribution systems

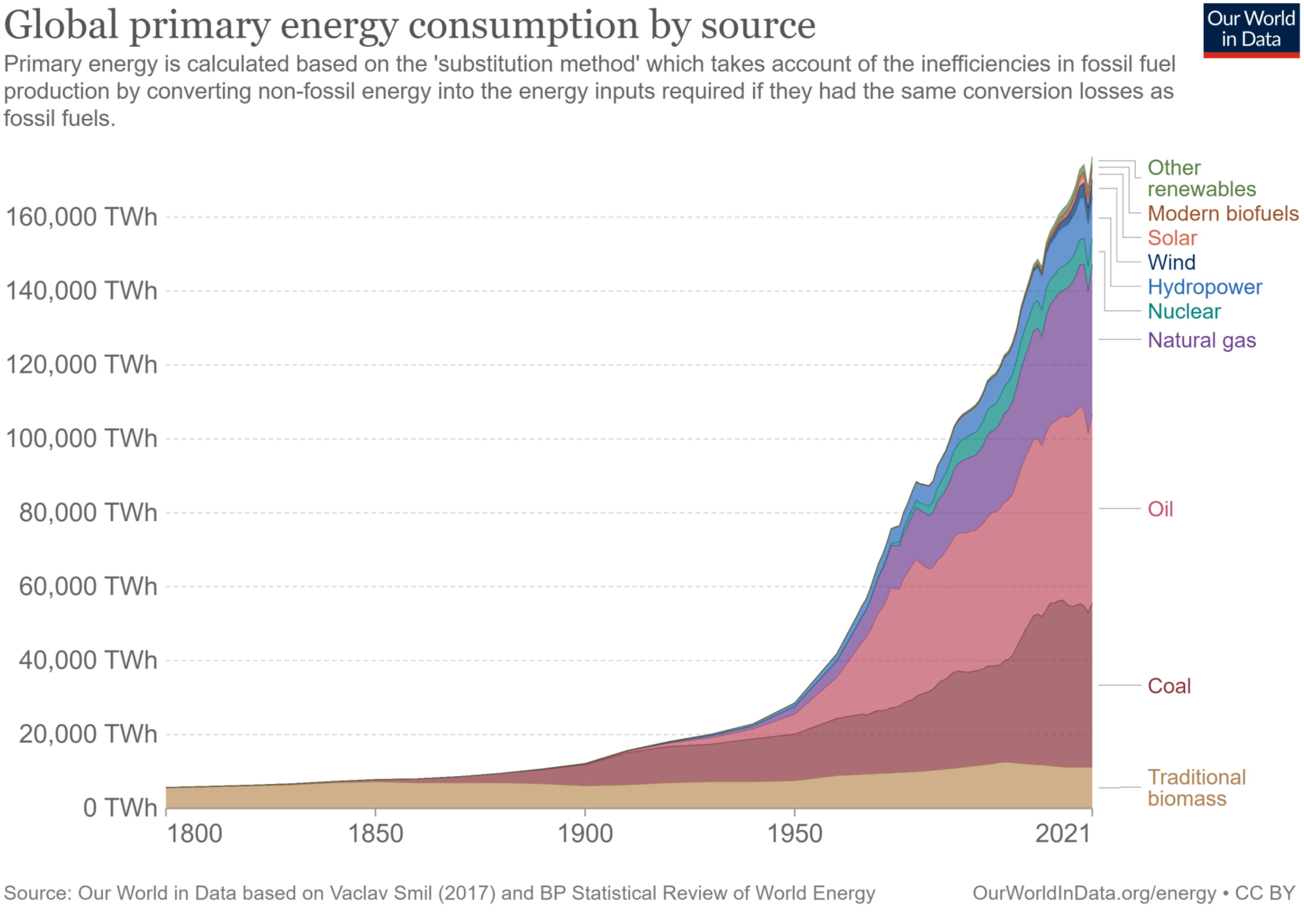
Centralized

- Classic system, a few or a dozen large or very large sources generate energy.
- Energy is transported to consumers over long distances through transmission and distribution networks.
- Electrical energy is usually produced from conventional energy sources.

Distributed

- The generation of energy by small units or production facilities, directly connected to distribution networks or located within the consumer's power grid.
- Usually producing electricity from renewable or non-conventional energy sources, often combined with heat generation (distributed cogeneration).

Share of sources in electricity „production”

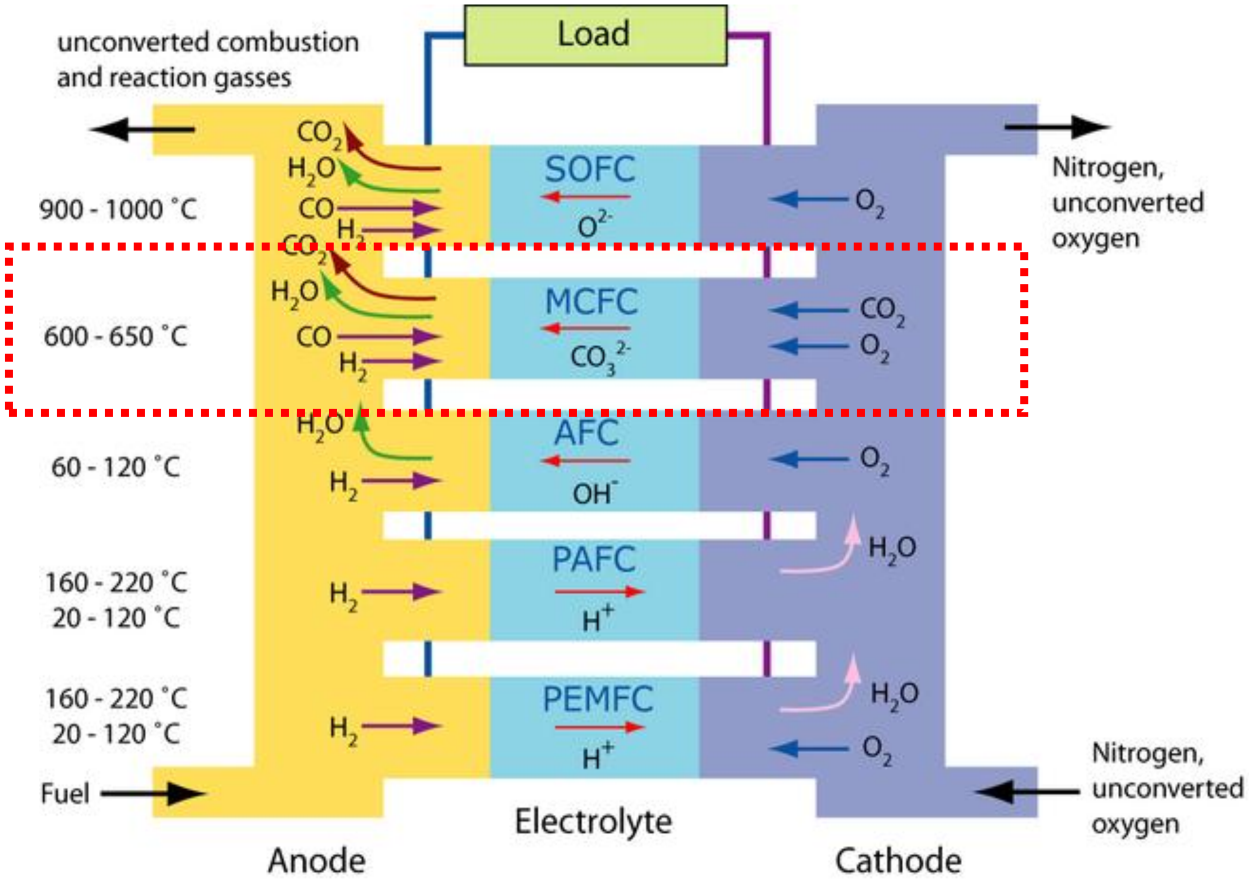


Various conversion energy technologies

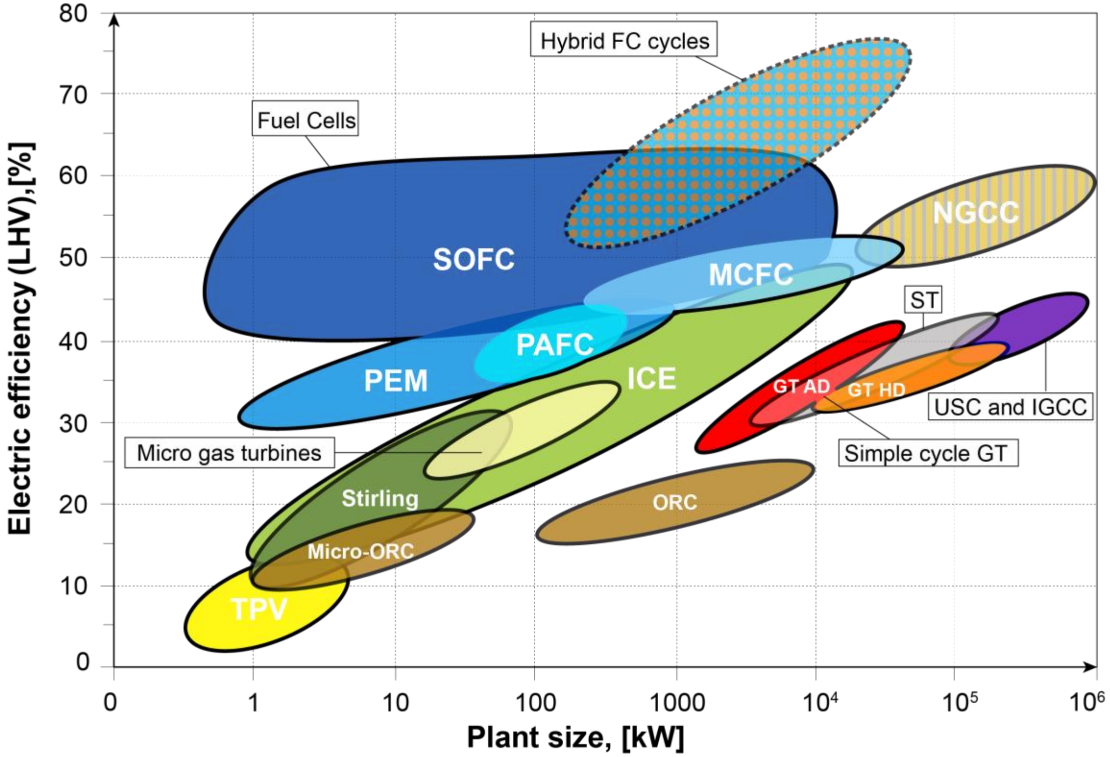
Energy source	Sposób generacji energii elektrycznej	Theoretical efficiency[1]	Zagrożenie dla środowiska
Water	Water turbine	90-95%	Ecosystem change, methane emission
Hydrogen, amonia, hydrocarbons	Fuel cells	40-60%	CO_2 emission when hydrocarbon used
Coal/oil/gas	Turbine	40-45%	Emision of gasous and Particulate Matter(PM) pulutions
Nuclear power	Reactor, Turbine	40%	Radioactive waste
Wind	Wind turbine	35%	Threat to fauna
Biomas	Turbine	35%	Emission of gases and Particulate Matter(PM)
Sun	Photovolatics	15-25%	-
Geotermia	turbina	15%	Contamination of groundwater, soil cooling

Basing on: [1] https://www.mpoweruk.com/energy_efficiency.htm

Fuel Cells - principles



Fuel cells are classified primarily by the kind of electrolyte



https://www.gecos.polimi.it/research-areas/hydrogen-fuel-cells-and-electrochemical-energy-systems/

Fuel cell overall efficiency

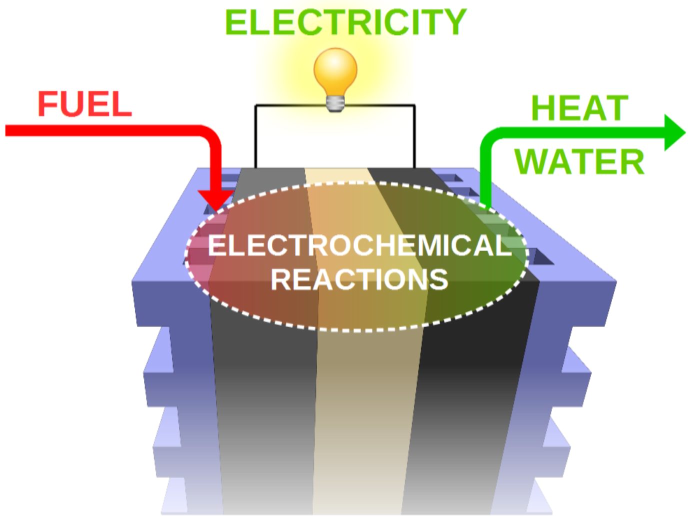
Fuel Cells - principles

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/ or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Source: US DOE (2010). *Fuel Cell Factsheet*

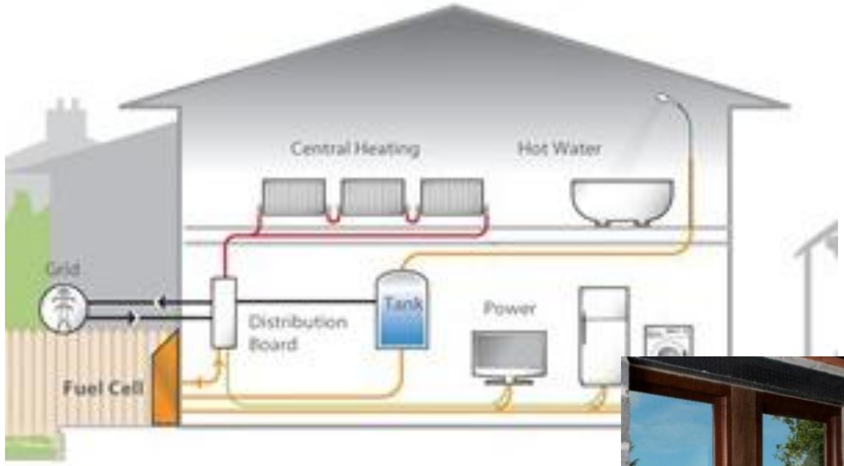
High-temperature fuel cells

Molten carbonate fuel cells (MCFCs) are the one of the most promising high efficiency and sustainable power generation technologies. MCFCs convert chemical energy of **fuel (hydrogen)** into **electricity, heat and water** through electrochemical reactions.



Main features:

- 300 kW–2.8 MW units, commercially available,
- combination of heat and power with gas expansion turbine delivers up to 65% efficiency,
- fuels: natural gas, anaerobic digester gas with internal reforming, sewage gas, natural gas and biogas compatible,
- average 10 000h lifetime,
- possible to employ in electrical utilities, industrial, and military applications.



◄▼ **Residential**

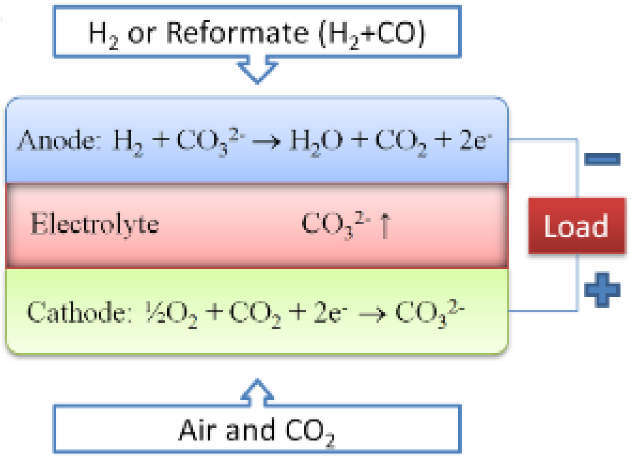
▼ **Commercial**

The world's largest operating fuel cell power plant (59 MW), located in Hwaseong, South Korea

Source:E4Tech http://www.fuelcelltoday.com

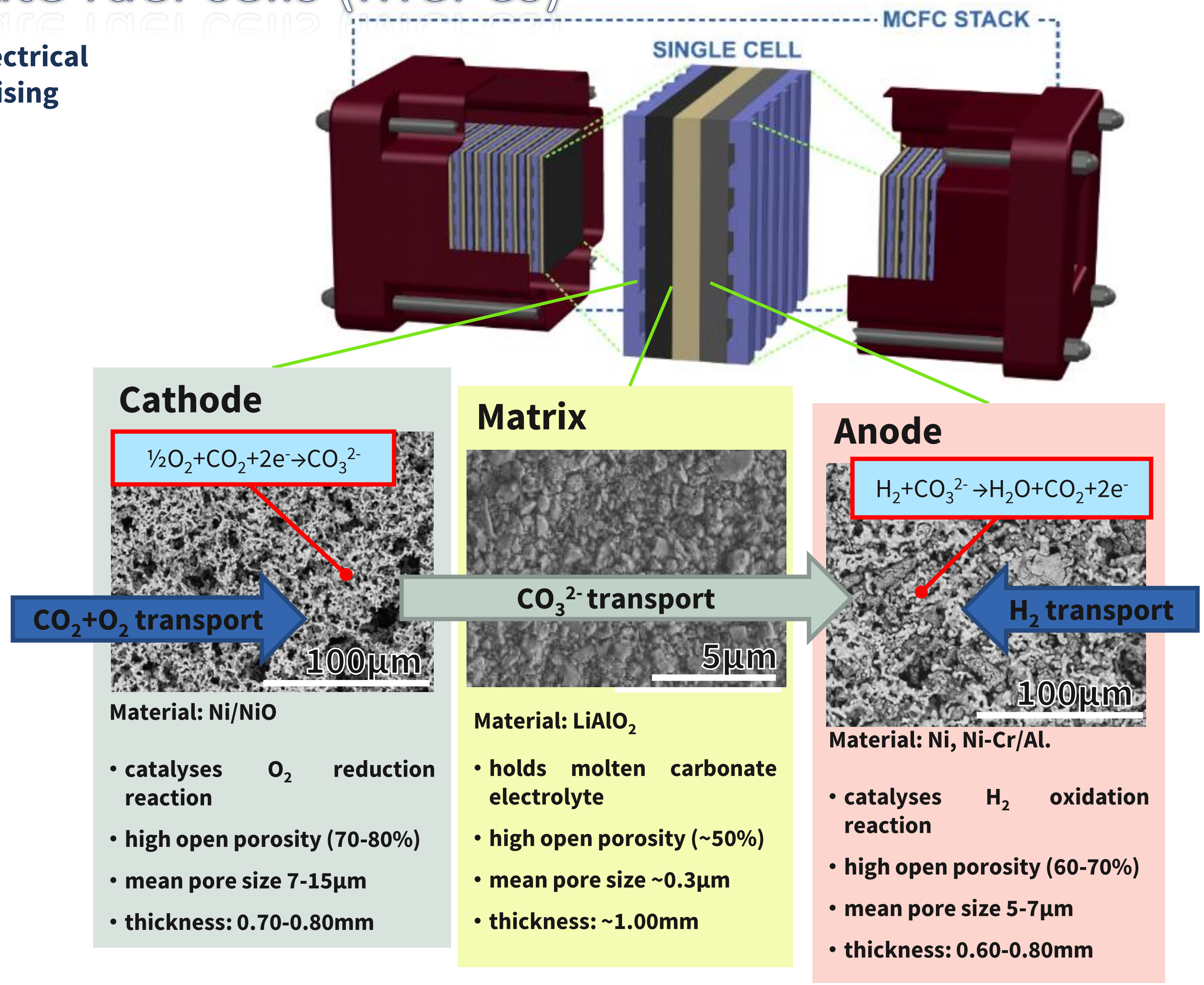
Materials for molten carbonate fuel cells (MCFCs)

Molten carbonate fuel cells are highly efficient **chemical to electrical energy converters** and emerges as the one of the **most promising sustainable power generation technologies**.

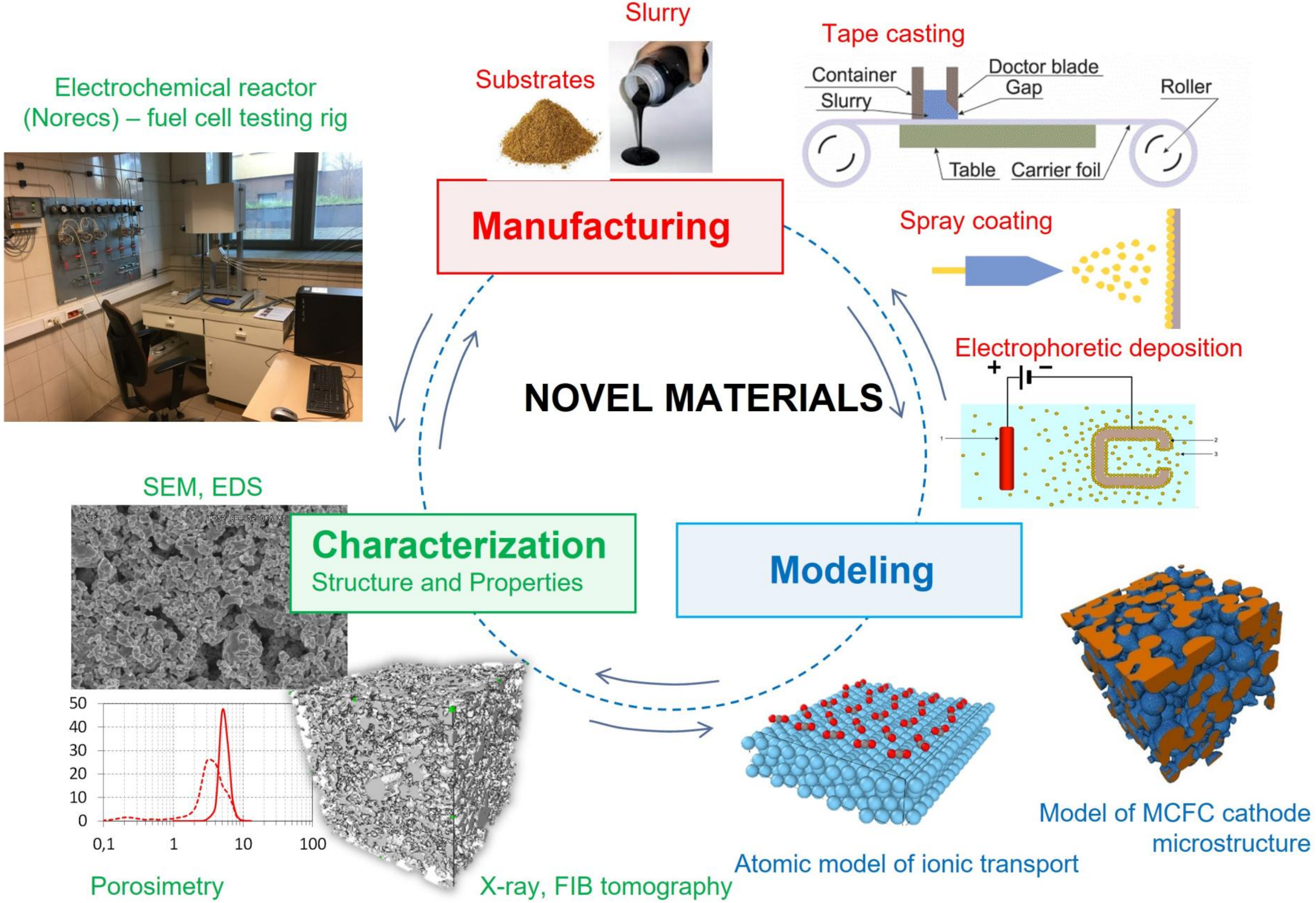


MCFC stacks are assemblies of **single cells**, where each single cell comprises of **porous** components:
- **cathode,**
- **anode,**
- **electrolyte matrix.**

The **electrolyte** – mixture of $(Li/K)_2CO_3$ or $(Li/Na)_2CO_3$ – is kept in molten state in MCFC operating conditions (600-700 °C).



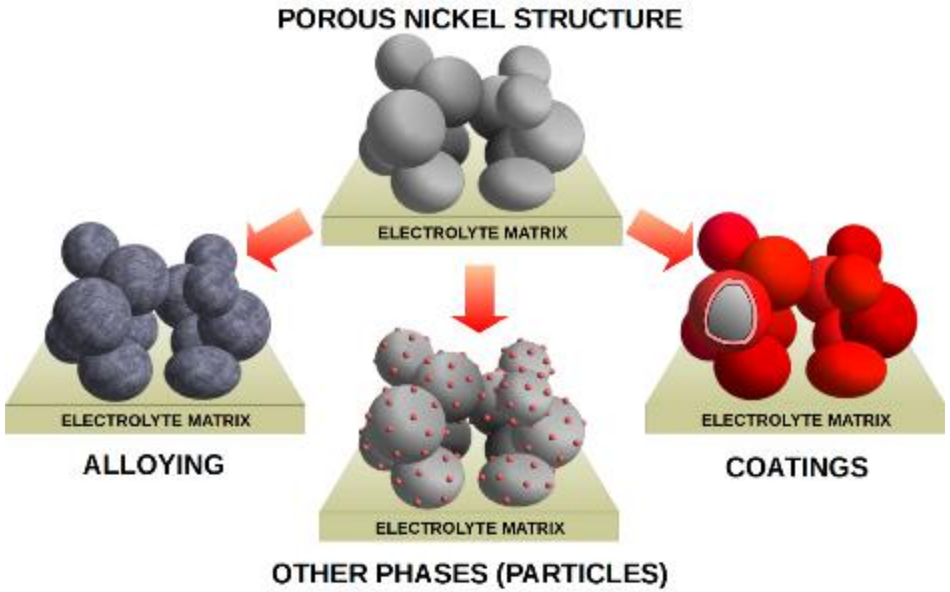
Concept for materials development



Concept for materials development - fabrication

Two main factors governing the performance of molten carbonate fuel cell materials

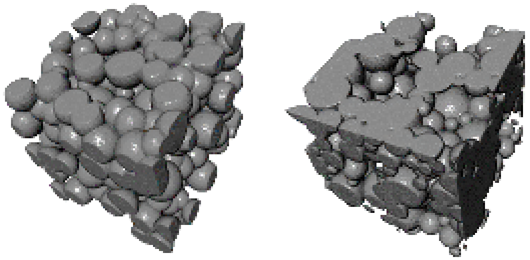
CHEMICAL COMPOSITION



MICROSTRUCTURE

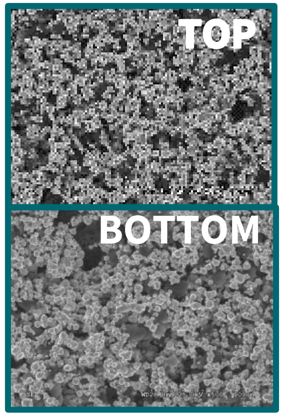
Isotropic

modification of pore size distribution, porosity with porogen additions



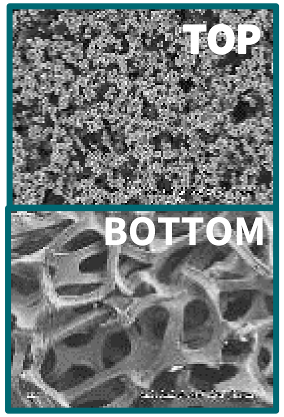
mono- vs. bi-modal

Layered



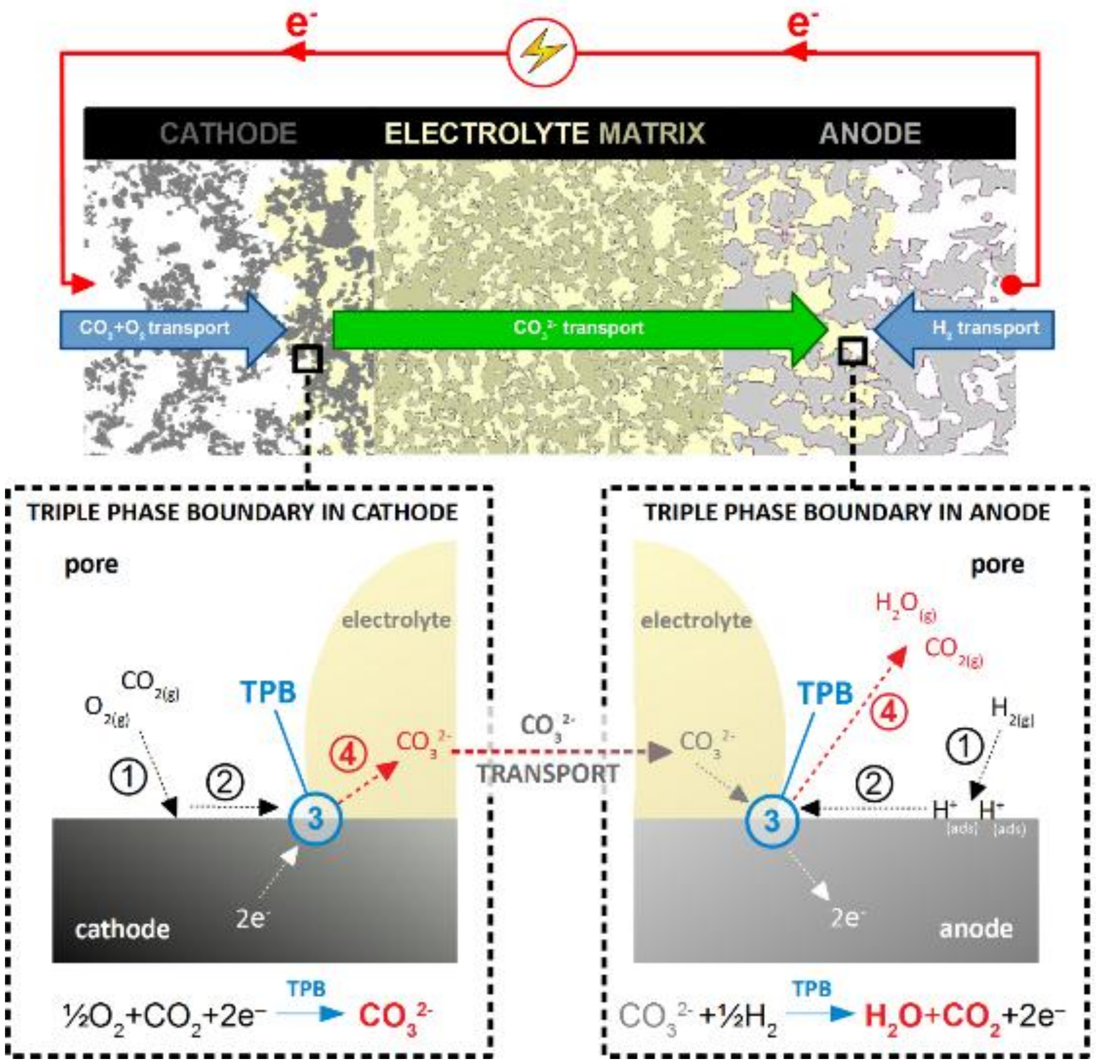
Tape cast layers

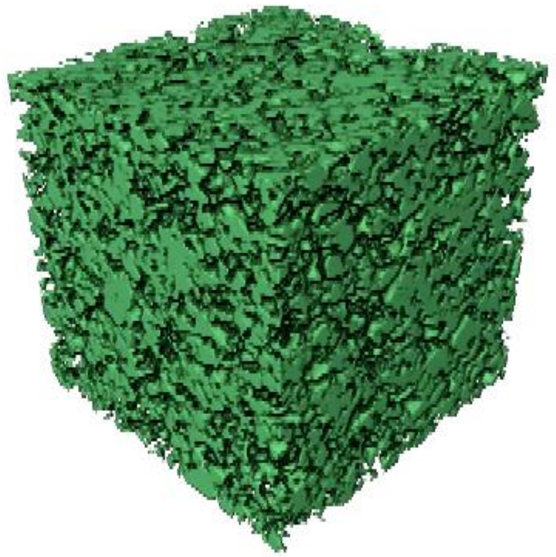
vs



Tape cast layer onto foam support

Molten Carbonate Fuel Cell - Processes





Elemental reaction steps:

① Adsorption of molecules

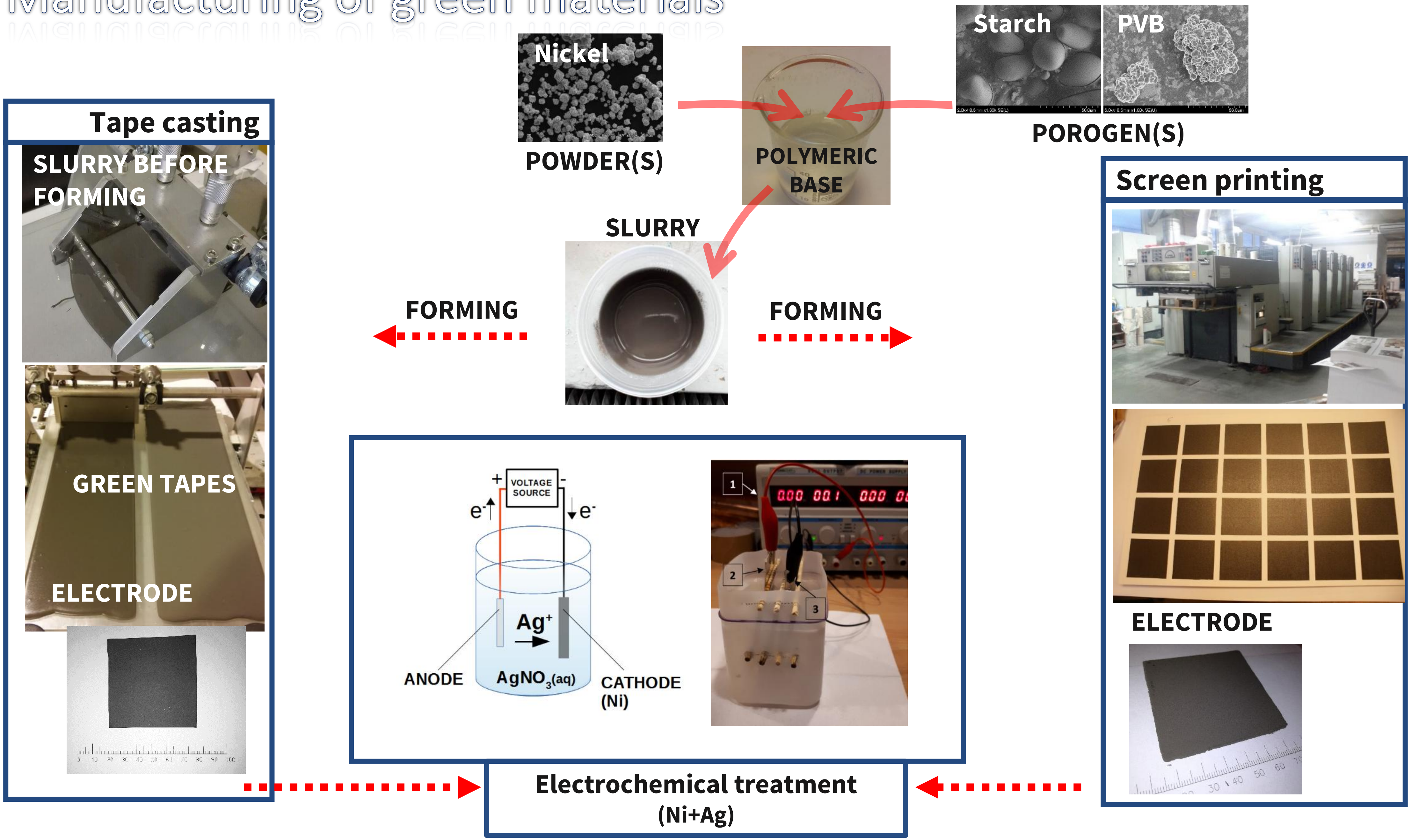
② Surface diffusion

③ Reaction at TPB

④ Desorption of products

The open-porous microstructure, apart from the chemical composition, is of great importance for the fuel cel performance.

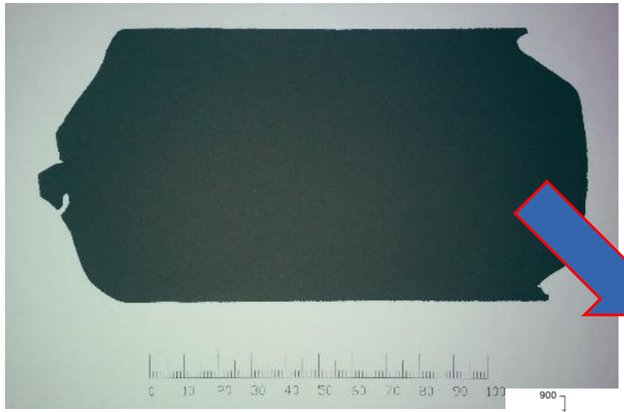
Manufacturing of green materials



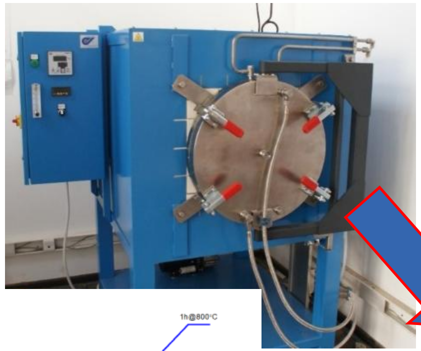
Heat treatment

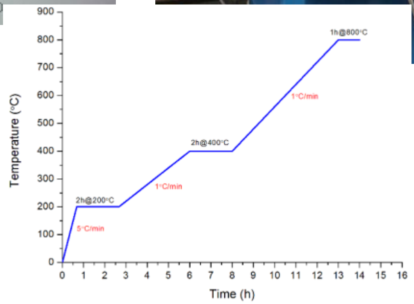
Heat treatment of green tapes can be separated in two steps:
1) removing volatile content and binder residues,
2) sintering of powders

GREEN TAPE

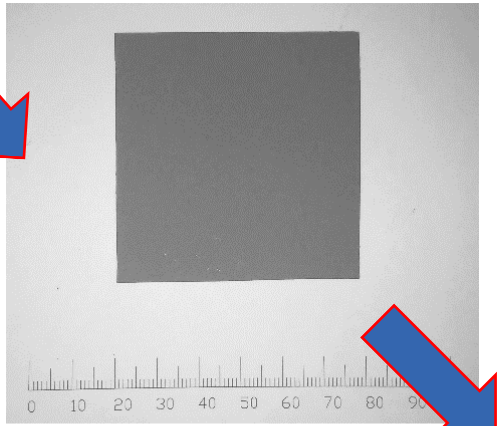


FIRING

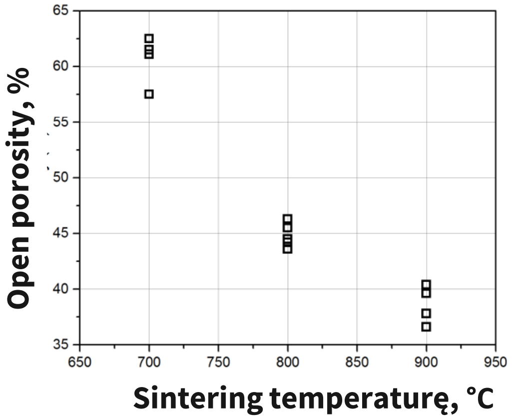




ELECTRODE



CHARACTERIZATION AND TESTING



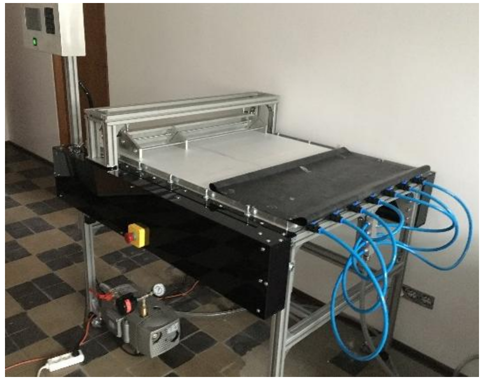
Open-porous structure of MCFC components is obtained after sintering. Porosity level is an effect of slurry composition and parameters of heat treatment: temperature (800-1000°C), time and atmosphere (commonly 100% hydrogen).

In the present work we sintered nickel-based porous electrodes using **N_2 + 5%H_2** atmosphere.

Fabrication - equipment

https://www.wim.pw.edu.pl/Badania-i-nauka/Aparatura-badawcza

Tape caster



High-temperature atmospheric tube furnace
Czylok, Poland

Ultrasonic spray coater Exacta Coat
SONO-TEK

Planetary ball mill
Retch PM400

Planetary Centrifugal Vacuum Mixer
Thinky ARV 930 TWIN

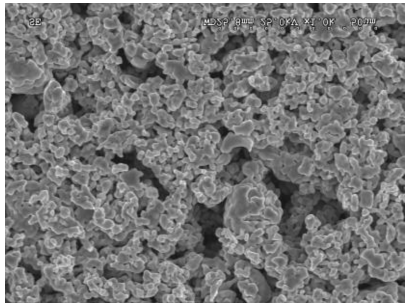
Programmable, atmosphere
furnace Czylok FCF-V70C/R

Microwave reactor
MAGNUM II, ERTEC-Poland

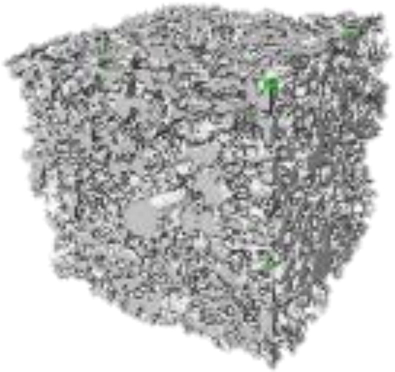
Characterization techniques

MICROSTRUCTURE CHARACTERIZATION

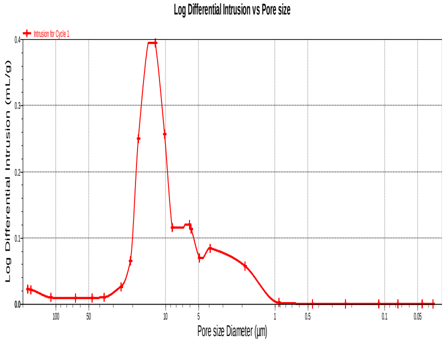
SEM
(morphology)



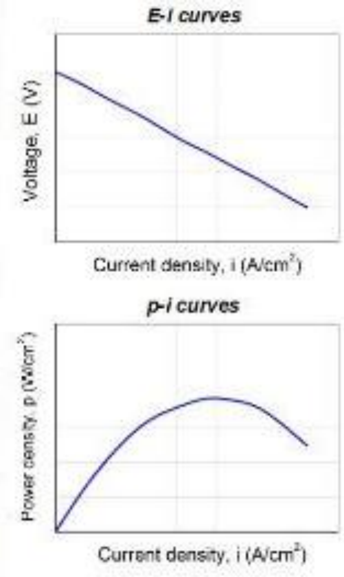
µCT
(3D imaging)



POROSIMETRY
(porosity, pore size distribution)

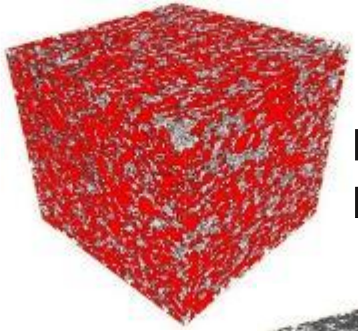


PERFORMANCE TESTING



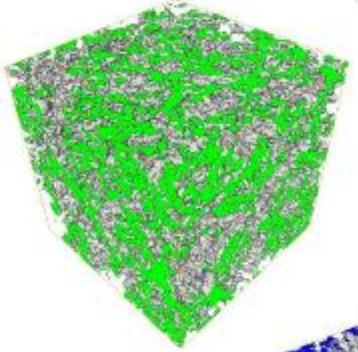
Milestone 1
Application of porogens

Wejrzanowski T., Haj Ibrahim S., Cwieka K., Loeffler M., Milewski J., Zschech E., Lee C-G., Journal of Power Sources 373 (2018) 85-94

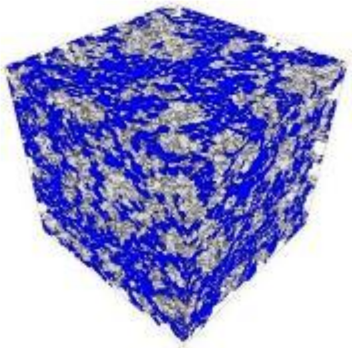


NO POROGEN

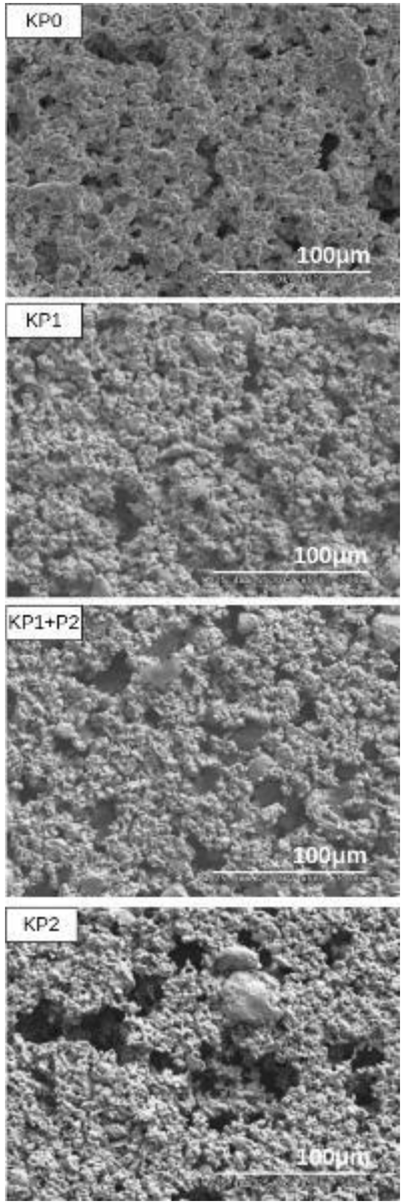
P1 (STARCH)

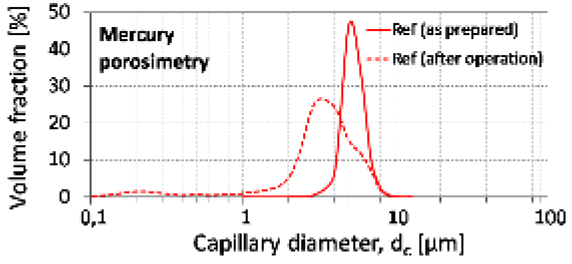


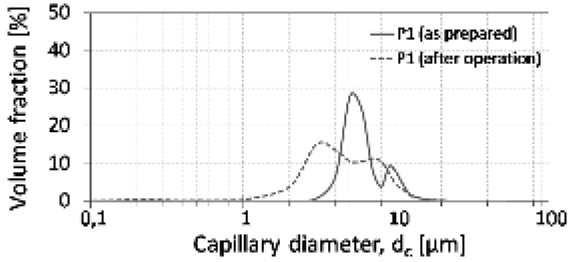
P1+P2

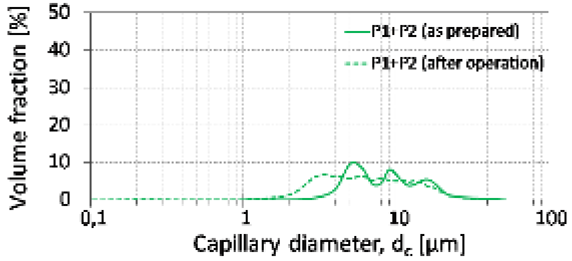


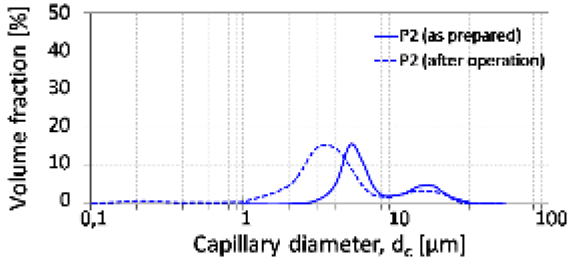
P2 (PVB)



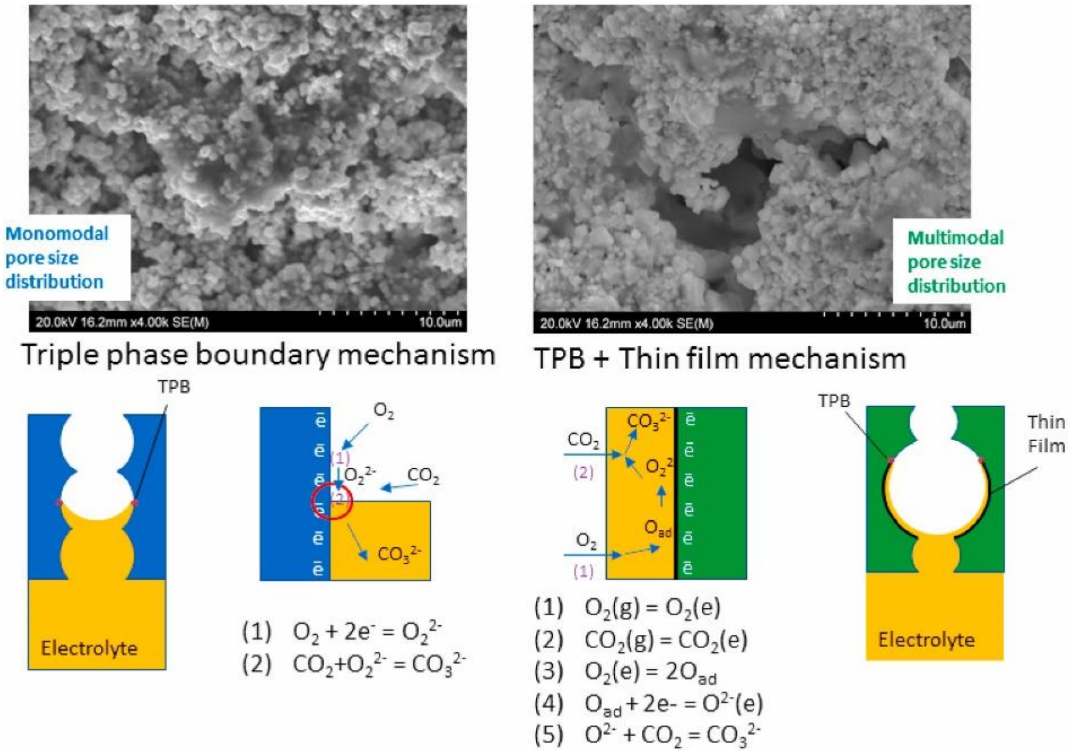


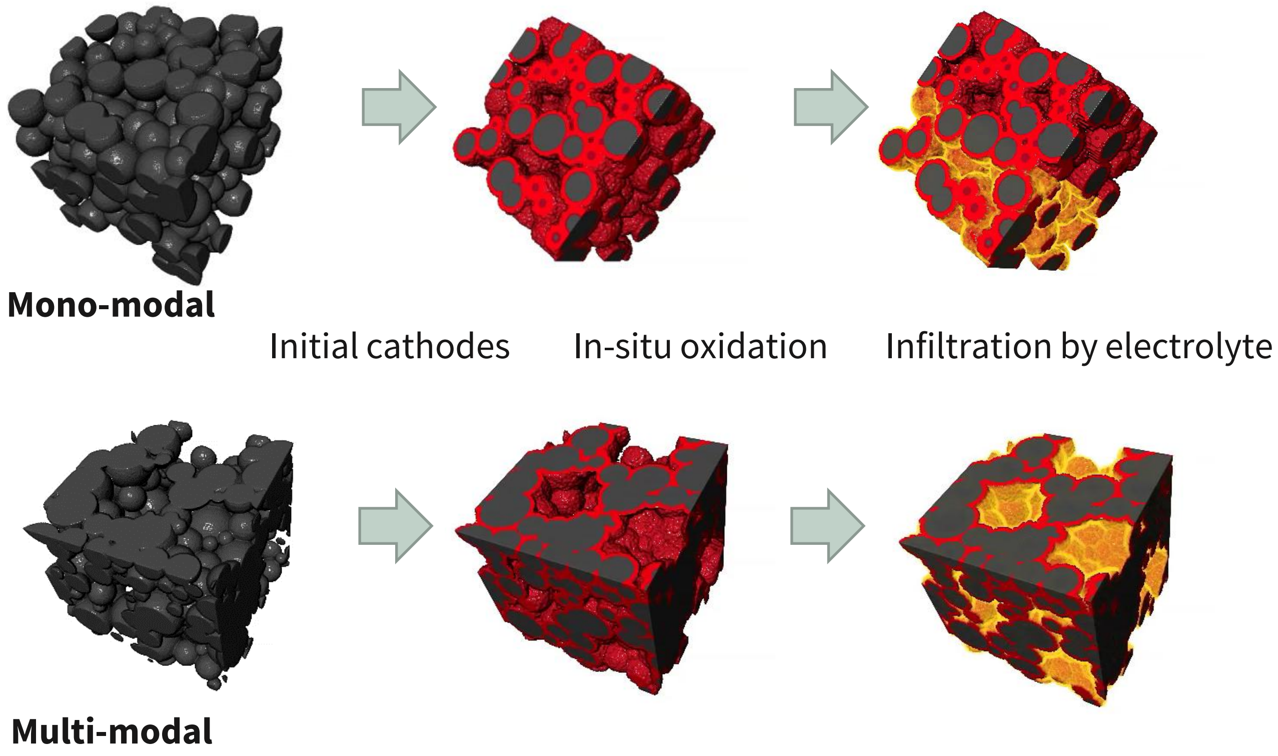


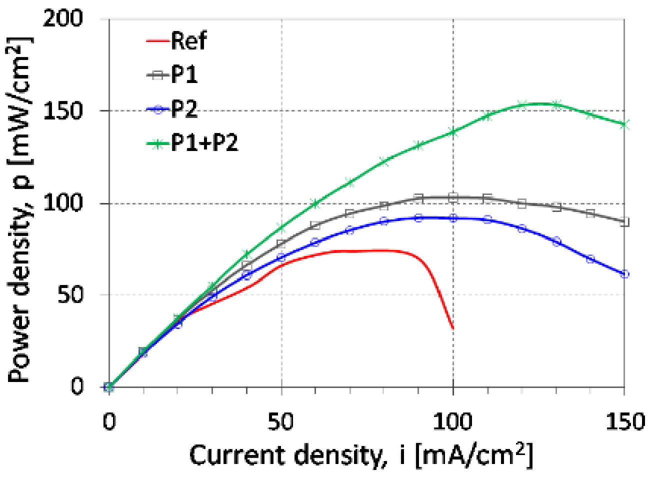


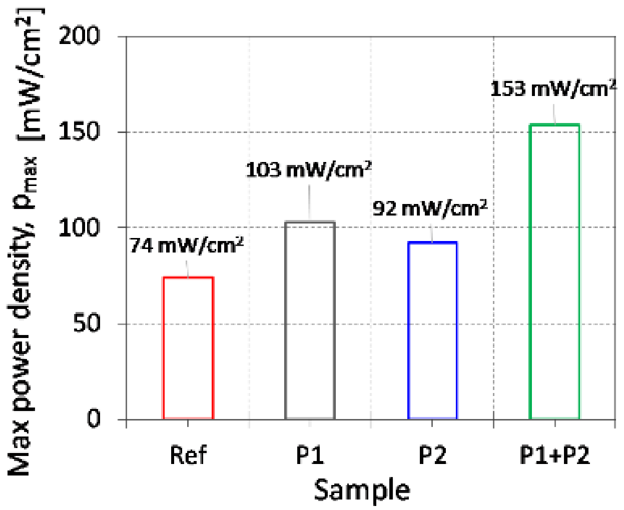


Milestone 1
Application of porogens







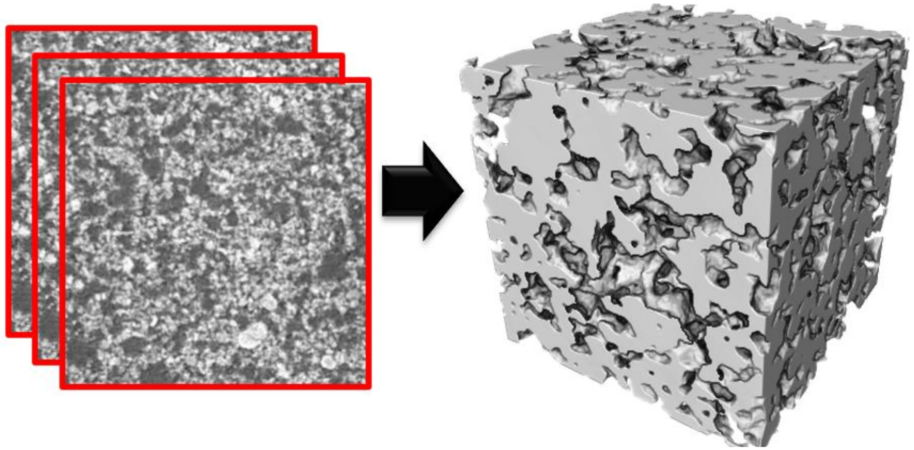


Multi-modal porosity of the cathode is **beneficial** for MCFC operation

Samih Haj Ibrahim, Tomasz Wejrzanowski, Pawel Sobczak, Karol Cwieka, Aleksandra Lysik, Jakub Skibinski, Graeme John Oliver, Insight into cathode microstructure effect on the performance of molten carbonate fuel cell, Journal of Power Sources 491 (2021) 229562

Milestone 1
Application of porogens

μ-CT



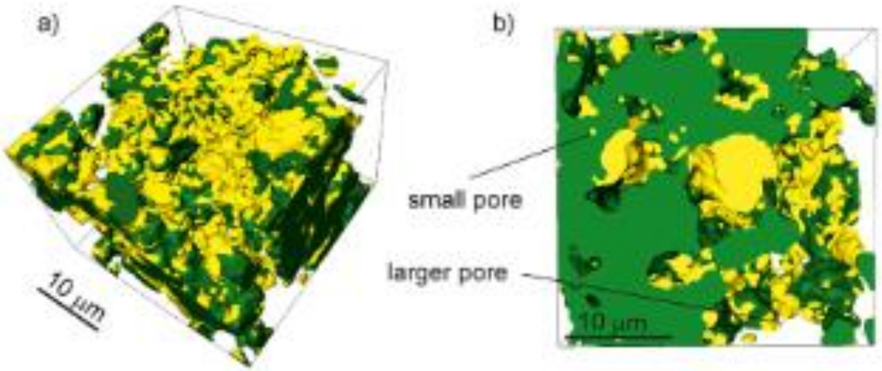
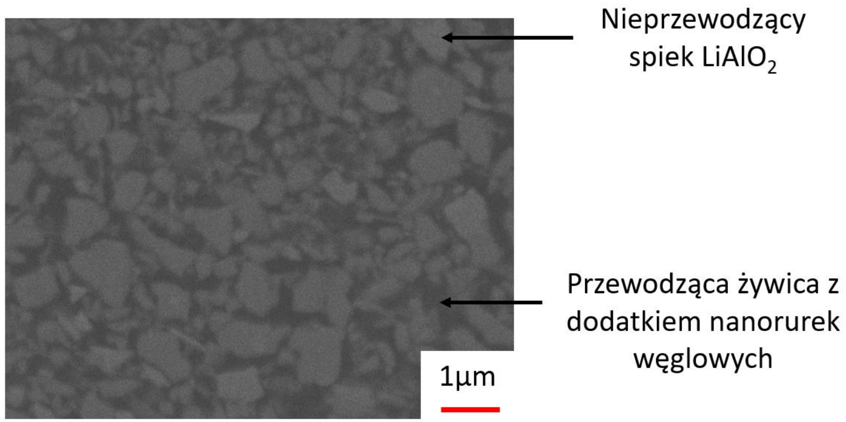
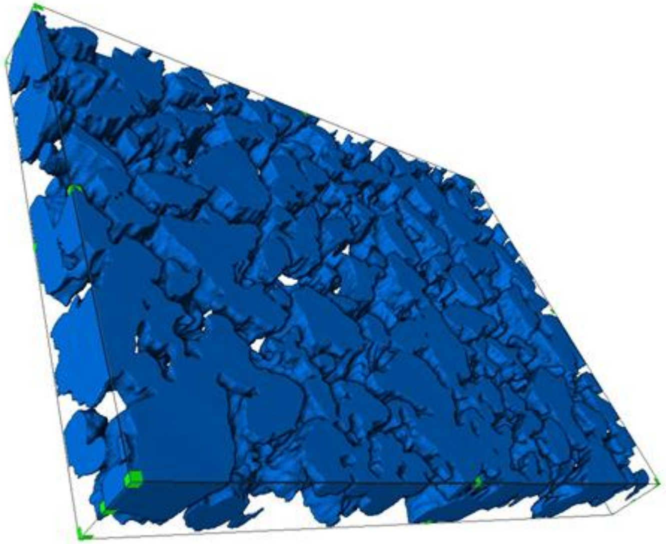


Figure 4. a) Reconstruction of the 3D microstructure of the cathode after operation. b) illustration of pore infiltration by the electrolyte – pores (transparent), NiO (green), electrolyte (yellow).

FIB-SEM

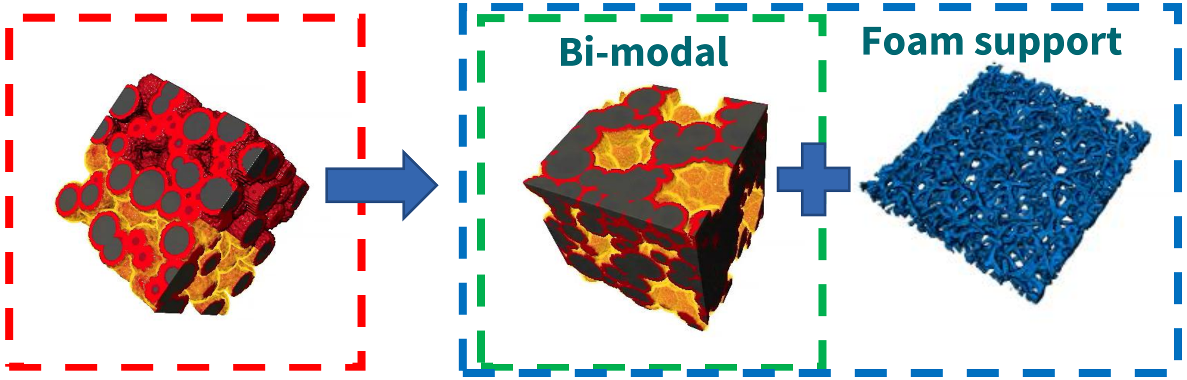


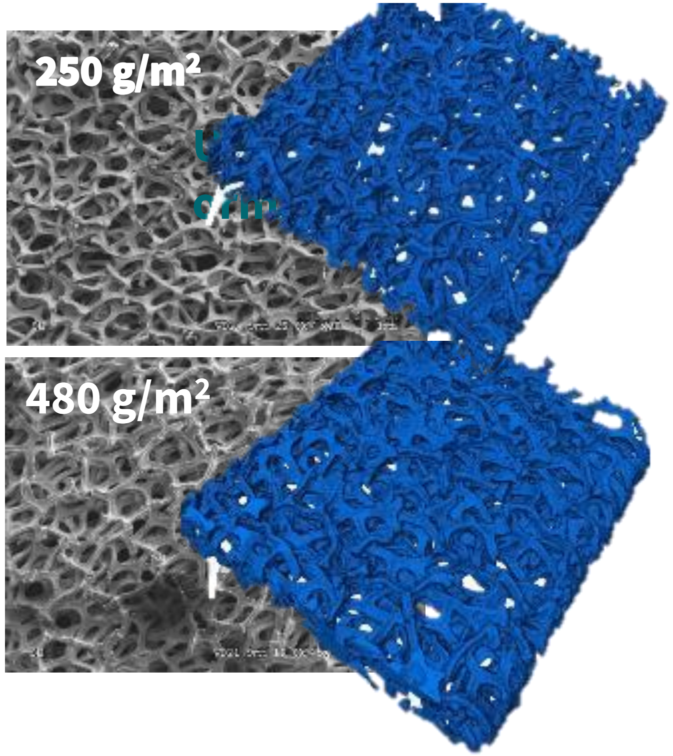


T. Wejrzanowski, J. Gluch, S. Haj Ibrahim, K. Cwieka, J. Milewski, E. Zschech, Advanced Engineering Materials 20 (2018) 1700909.

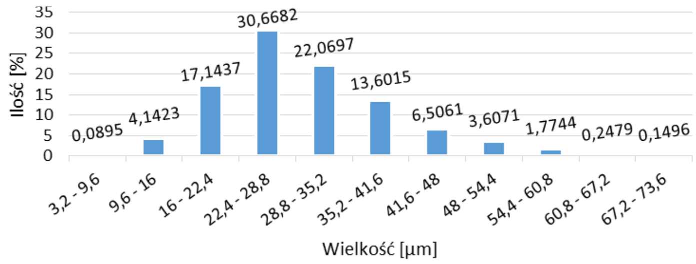
Milestone 2

Application of nickel foam support

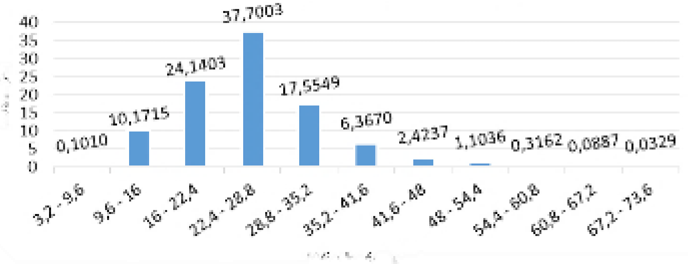




Pore size distribution in foam suport (250g/m²)



Pore size distribution in foam suport (480g/m²)

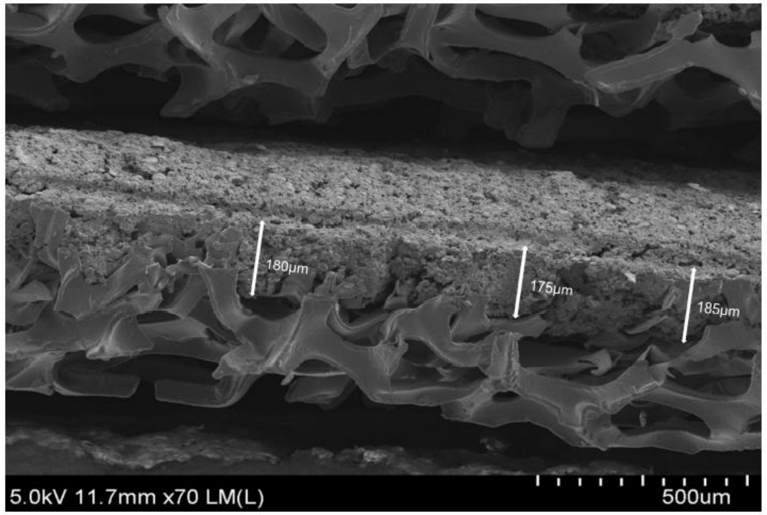


Lp.	Surface density $[g/m^2]$	Support thickness $[mm]$	Top layer thickness $[mm]$
1	250	0,5	0,4
2	480	0,5	0,4
3	250	0,5	0,3
4	480	0,5	0,3
5	250	0,5	0,6
6	480	0,5	0,6

	Open porosity [%]	
	Archimedes	µ-XCT
Foam 250 g/m²	89,02	80,19
Foam 480 g/m²	81,60	78,60
Top layer	67,35	n.a.

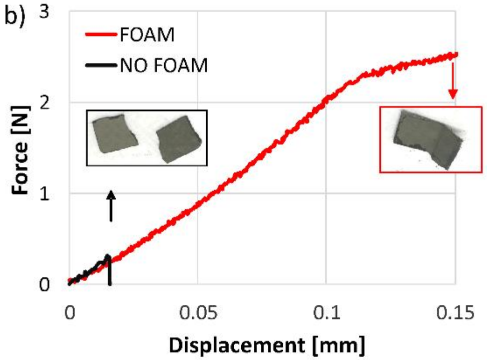
Milestone 2

Application of nickel foam support

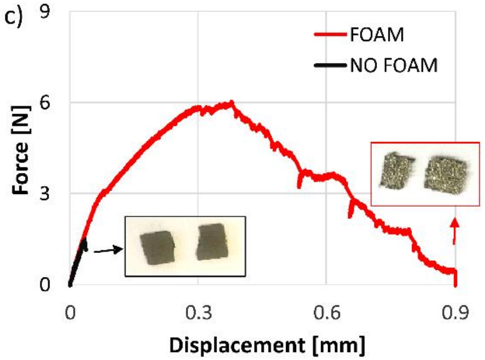


a)

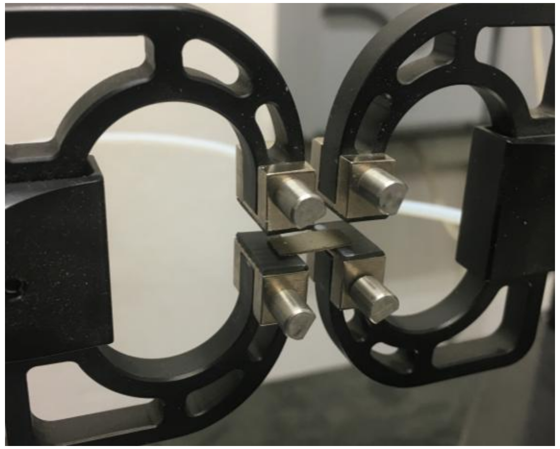
b)



c)



Mechanical testing

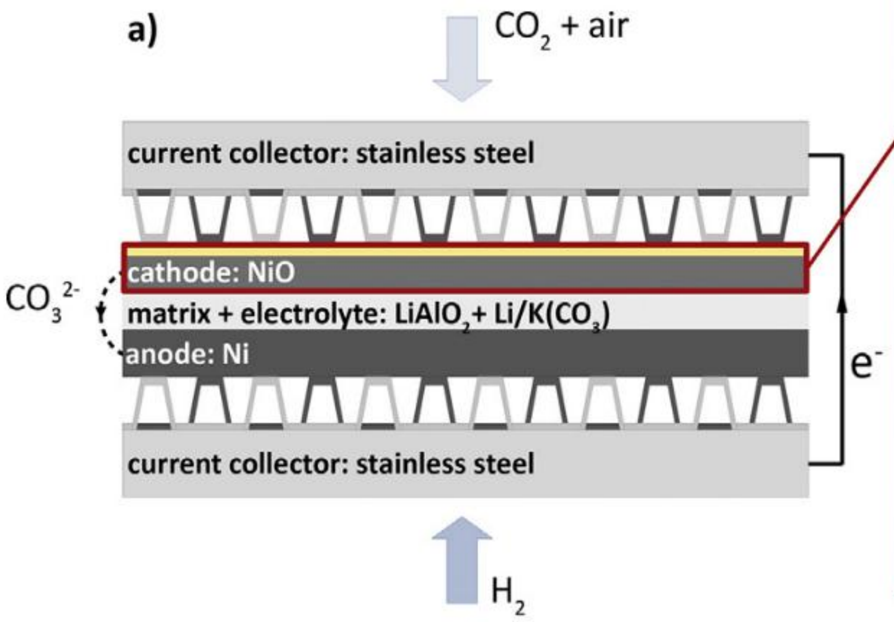


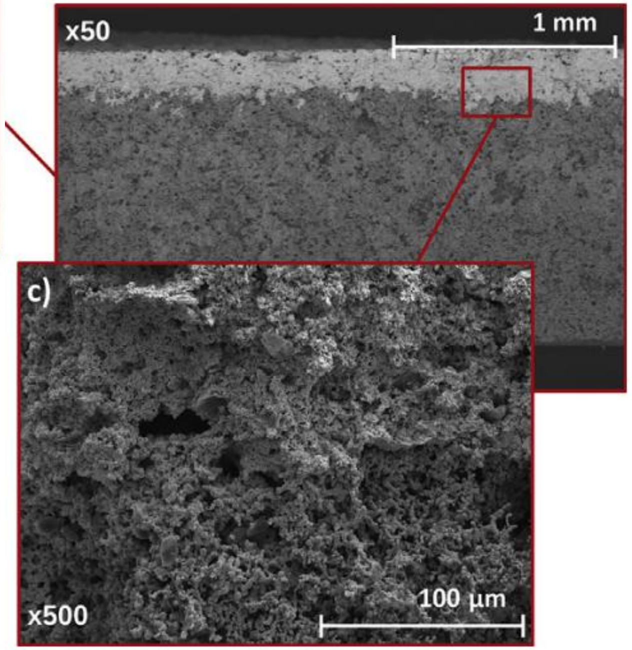
T. Wejrzanowski, K. Cwieka, J. Skibinski, T. Brynk, S. Haj Ibrahim, J. Milewski, W. Xing,
Metallic foam supported electrodes for molten carbonate fuel cells, Materials & Design 2020

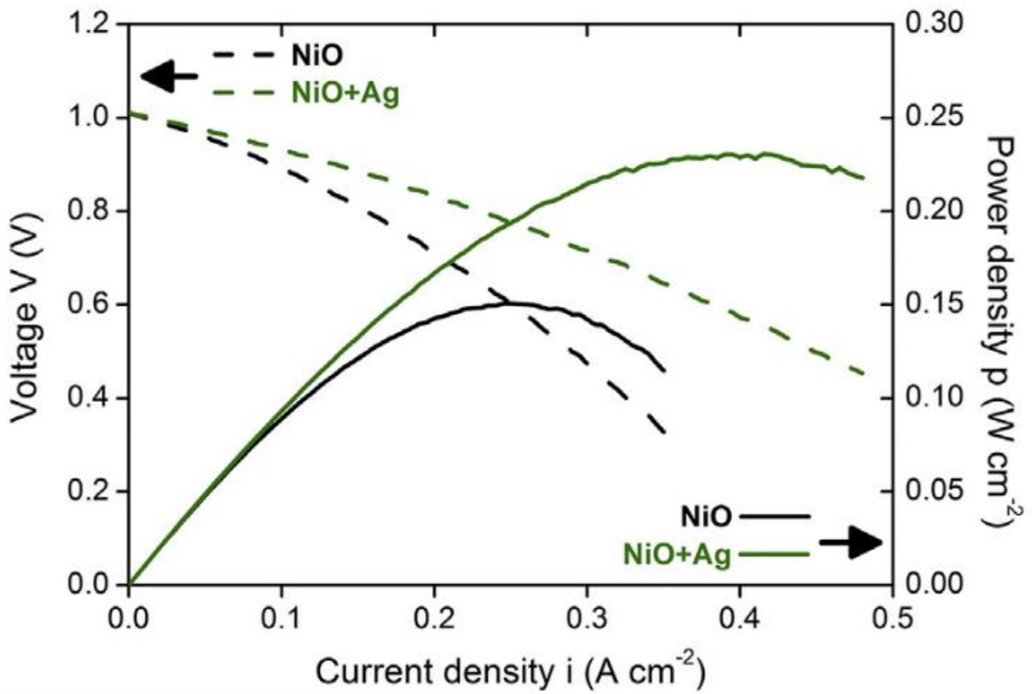
Patent: Pat.241140 „Elektroda węglanowego ogniwa paliwowego o zwiększonej wytrzymałości mechanicznej"

Milestone 3

Application of silver coating







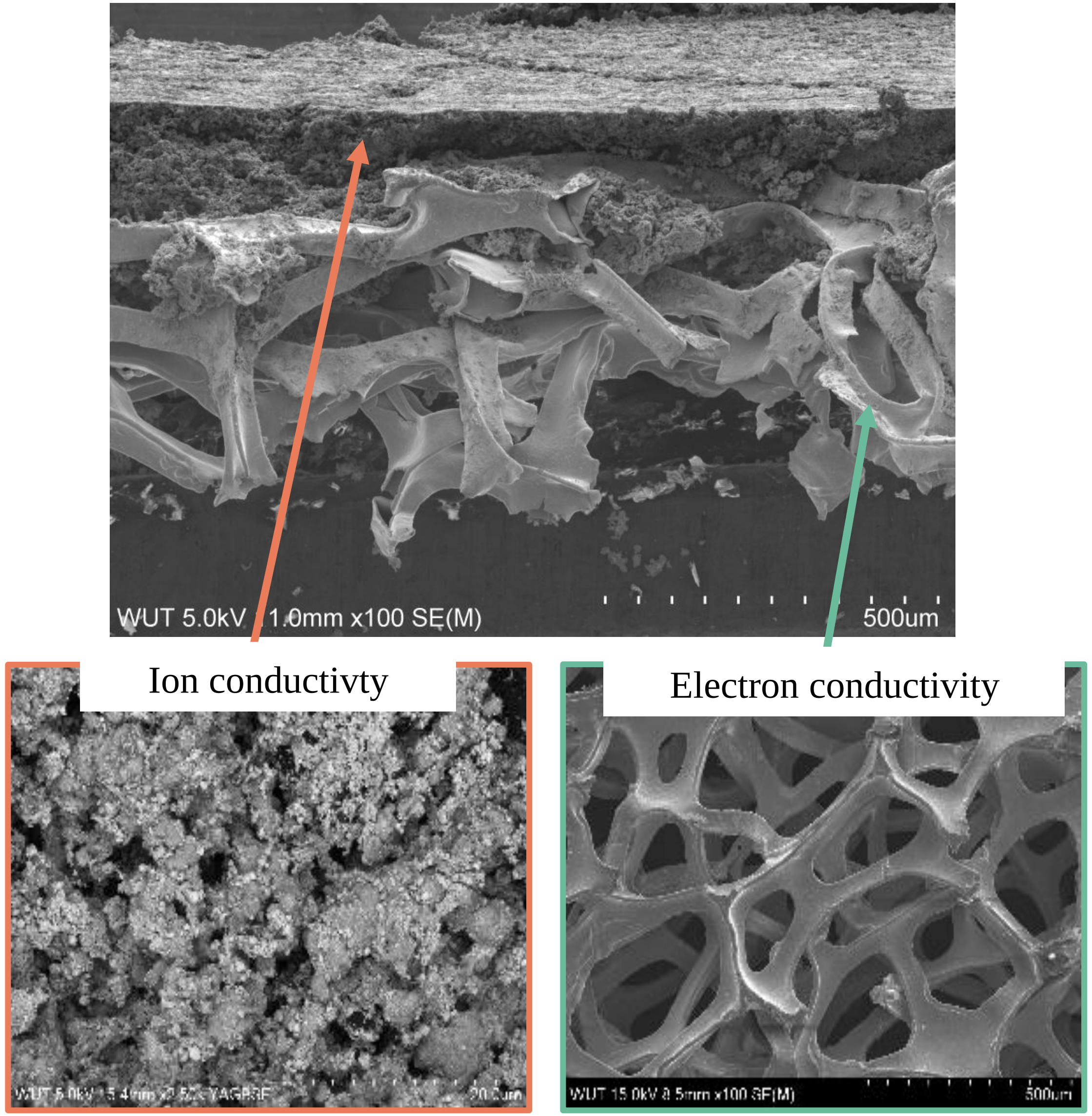
Aleksandra Lysik, Karol Cwieka, Tomasz Wejrzanowski, Jakub Skibinski, Jaroslaw Milewski, Fernando M. B. Marques, Truls Norby, Wen Xing, Silver coated cathode for molten carbonate fuel cells, June 2020, International Journal of Hydrogen Energy 45(38)

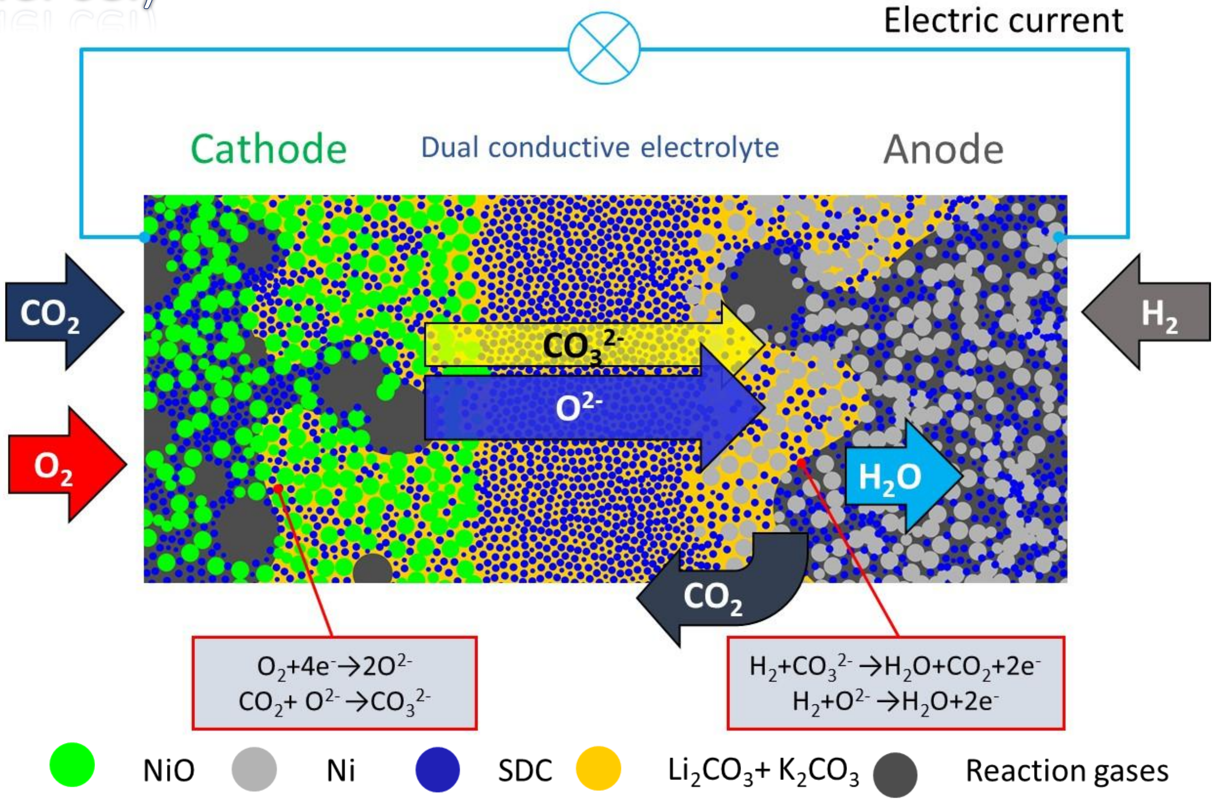
Karol Ćwieka, A Lysik, Tomasz Wejrzanowski, Truls Norby, Wen Xing, Microstructure and electrochemical behavior of layered cathodes for molten carbonate fuel cell, Journal of Power Sources 500 (2021) 229949

Patent: P.430869 Katoda węglanowego ogniwa paliwowego z warstwą spieku srebra

Milestone 4

Hybrid MCFC/SOFC = COFC (Carbonate oxide fuel cel)



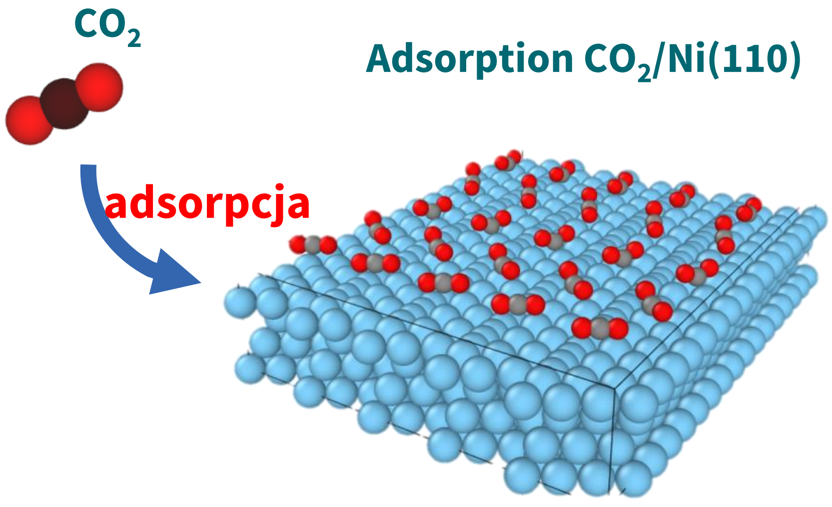


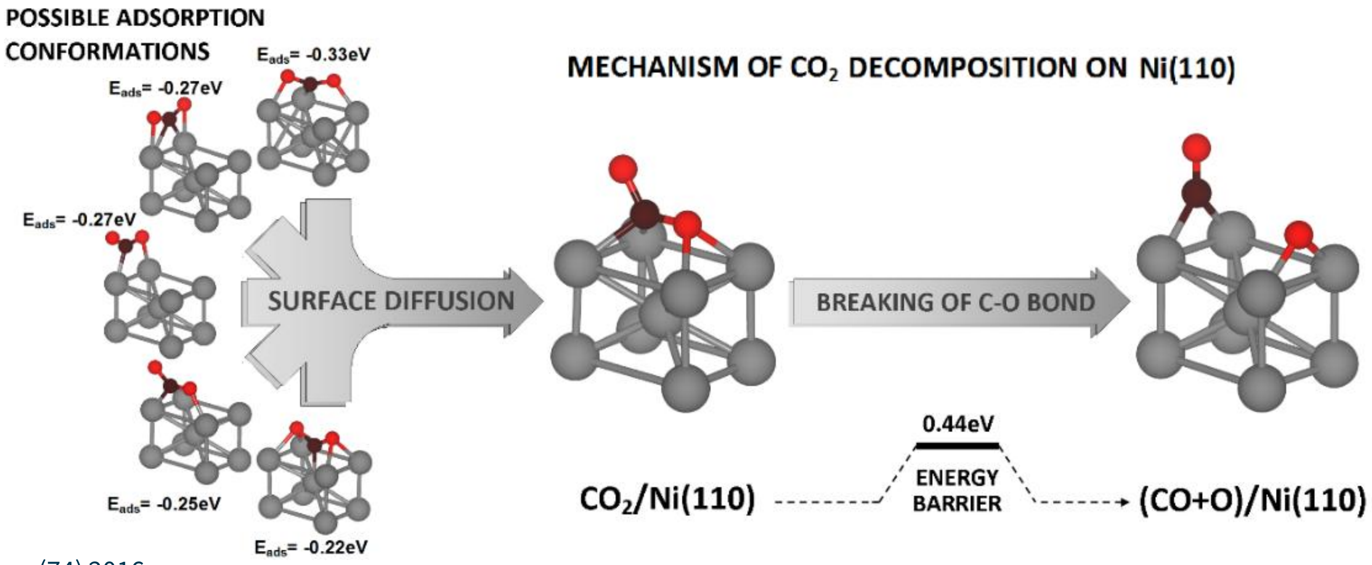
Komorowska, G.; Wejrzanowski, T.; Jamroz, J.; Jastrzębska, A.; Wróbel, W.; Tsai, S.-Y.; Fung, K.-Z. Fabrication and Characterization of a Composite Ni-SDC Fuel Cell Cathode Reinforced by Ni Foam. Materials 2022, 15, 4891. https://doi.org/10.3390/ ma15144891

Gabriela Komorowska, Jan Jamroz, Tomasz Wejrzanowski, Kamil Dydek, Rafał Molak, Wojciech Wróbel, Shu-Yi Tsai, Kuan-Zong Fung, Thermal treatment and properties of Ni-SDC cathode for high temperature fuel cells, Materials Science for Energy Technologies 6 (2023) 105-113

Multiscale modelling

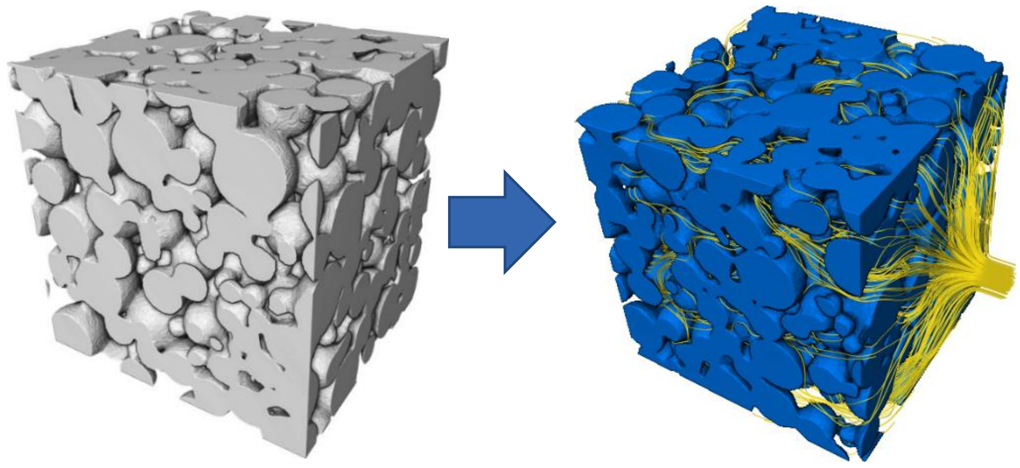
Atomic scale



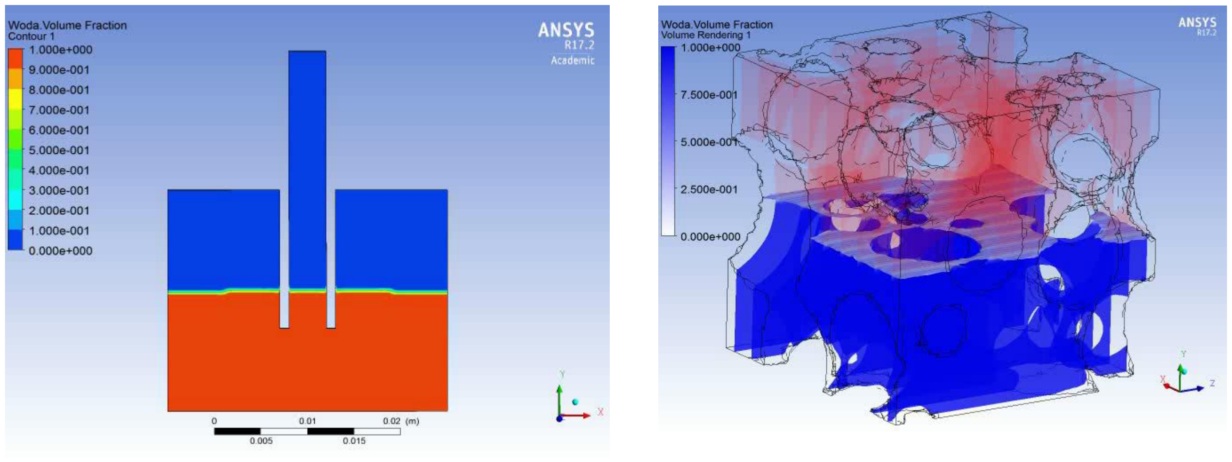


Czelej, K., Cwieka, K., Wejrzanowski, T., Spiewak, P., Kurzydlowski, K.J., Catal. Commun. (74) 2016

Mesoscale



Gas flow

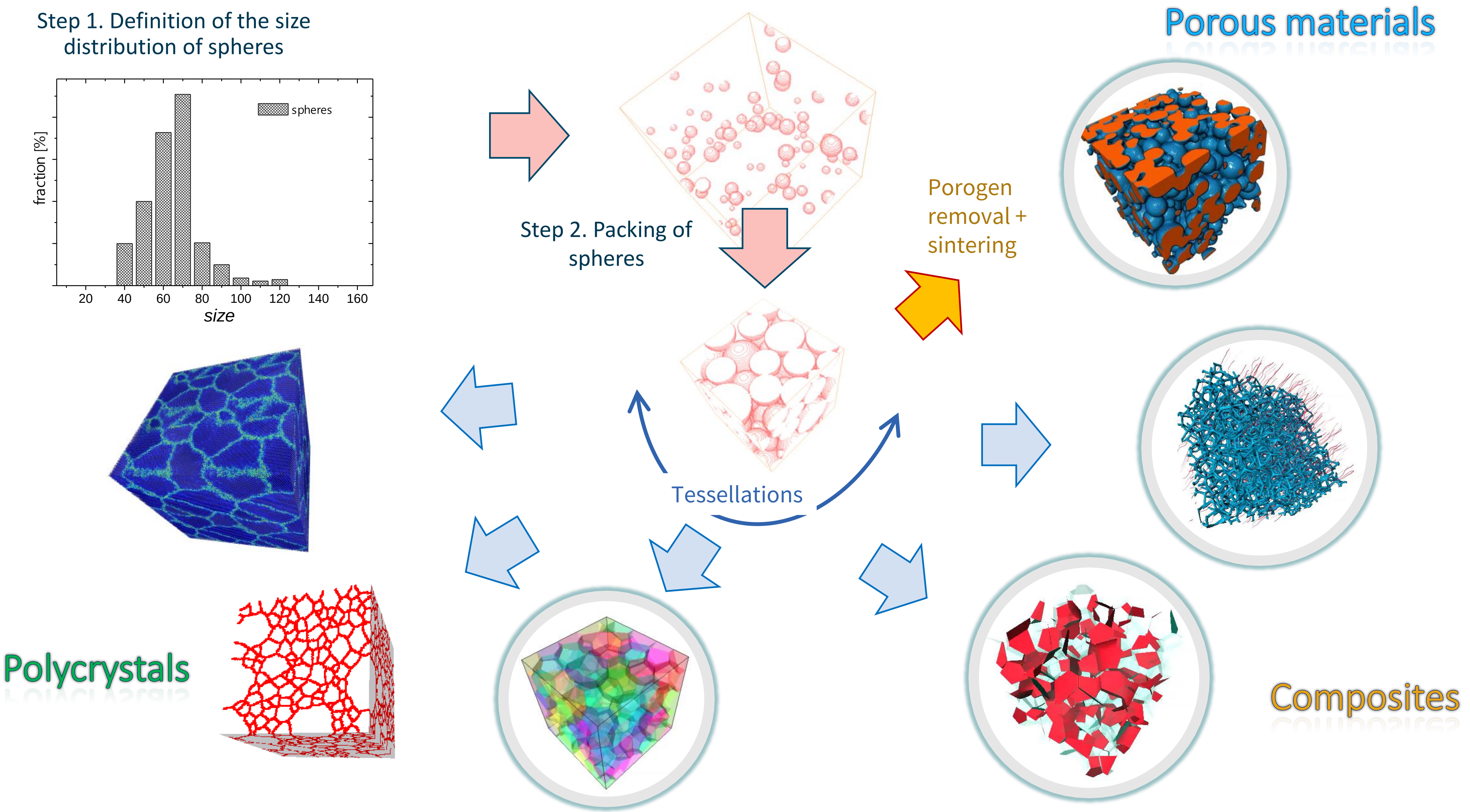


Liquid electrolyte infiltration

Haj Ibrahim S., Neumann M., Klingner F., Schmidt V., Wejrzanowski T., Materials and Design 133 (2017)

S. Haj Ibrahim, T. Wejrzanowski, P. Sobczak, K. Cwieka, A. Lysik, J Skibinski, G.J. Oliver, Journal of Power Sources 491 (2021) 229562.

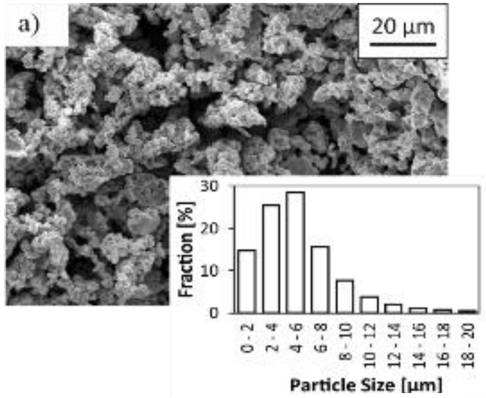
Microstructure modeling – general concept



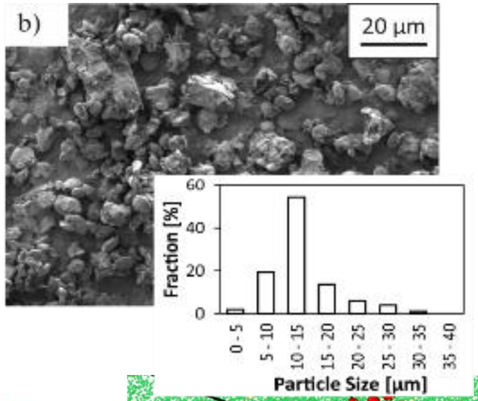
Molten Carbonate Fuel Cell

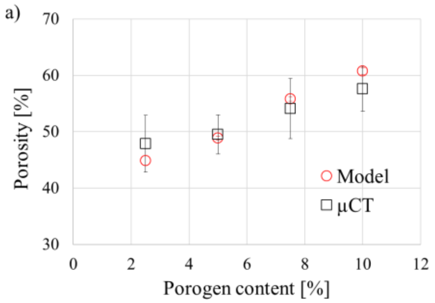
Modeling capillary effect

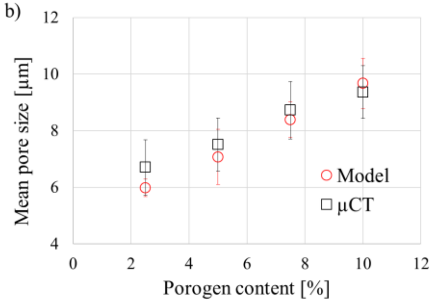
Nickel powder particles

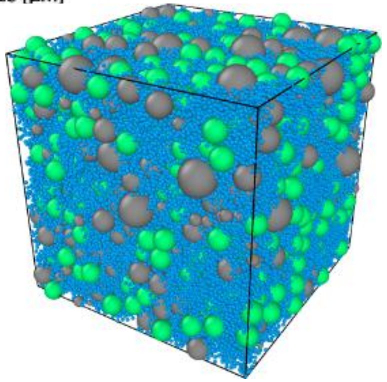


Porogen powder particles





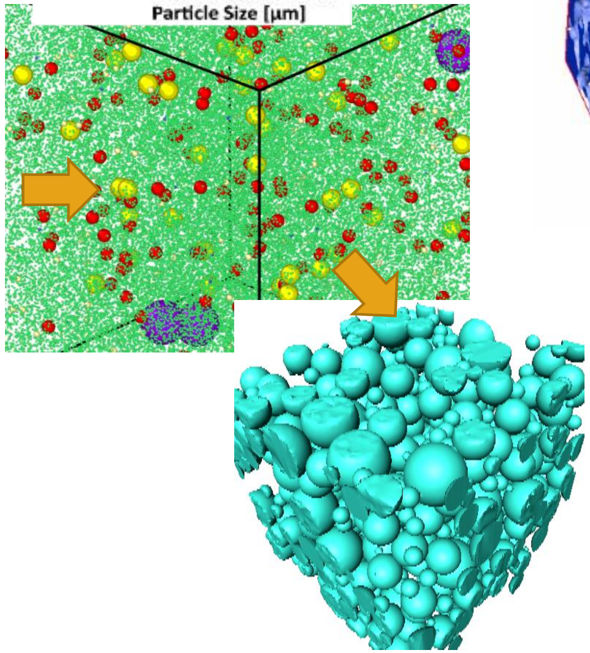


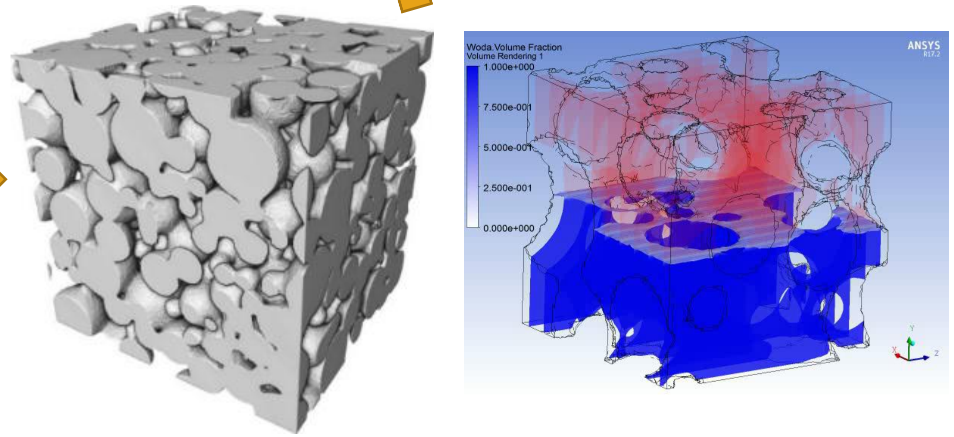


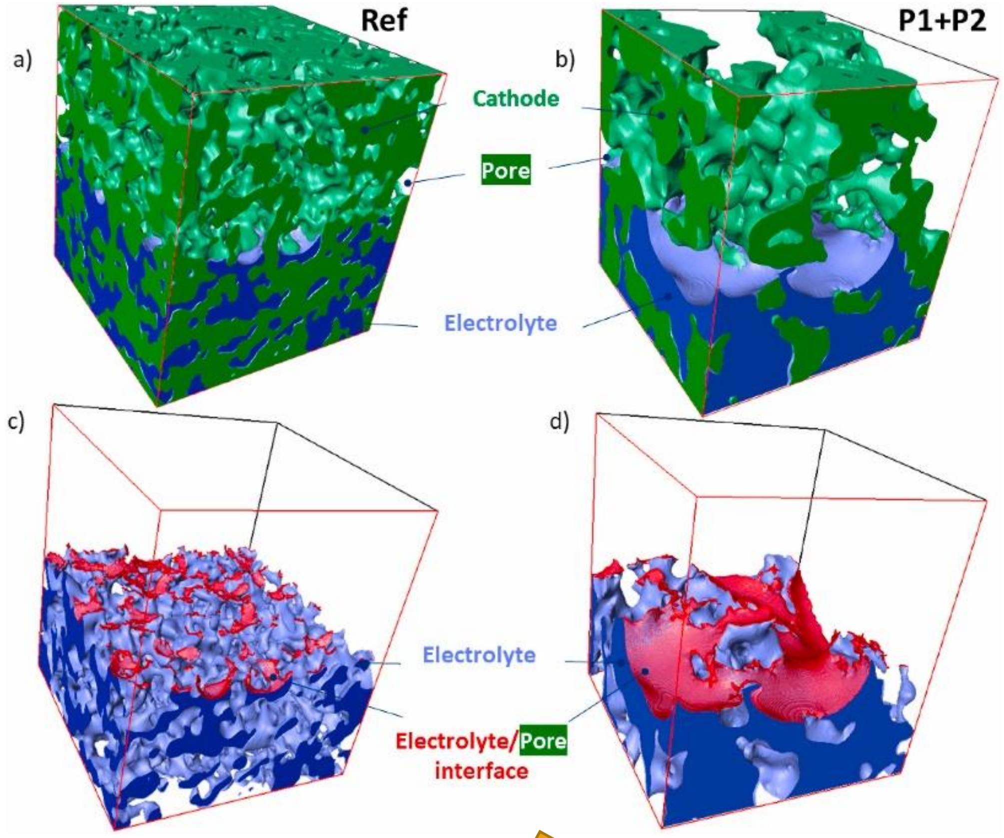
Nickel powder

Porogen particles

Liquid phase (polymeric base)



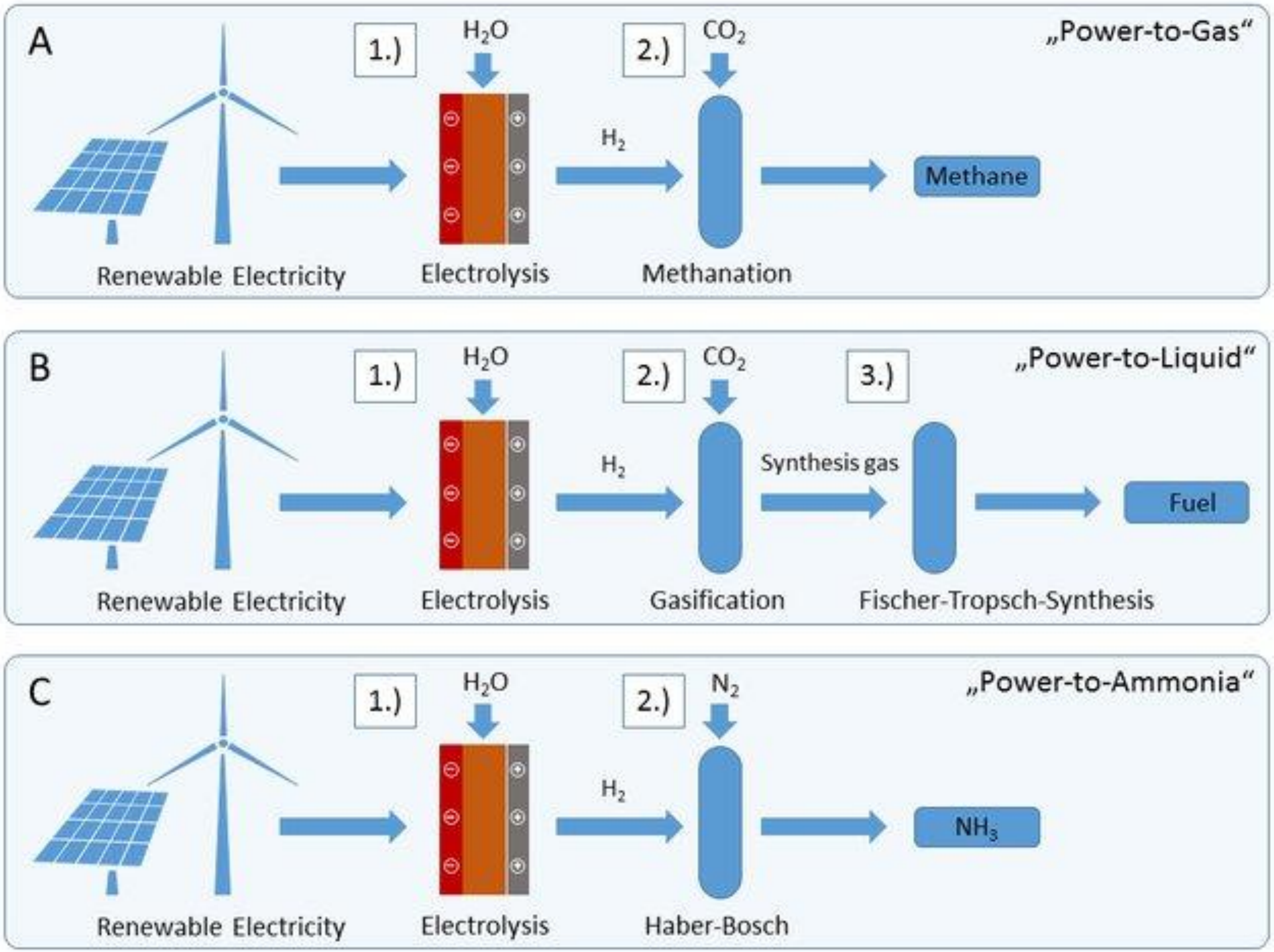




Wejrzanowski T., Haj Ibrahim S., Cwieka K., Milewski J., Kurzydlowski K.J., Journal of Power Technologies 96 (2016)

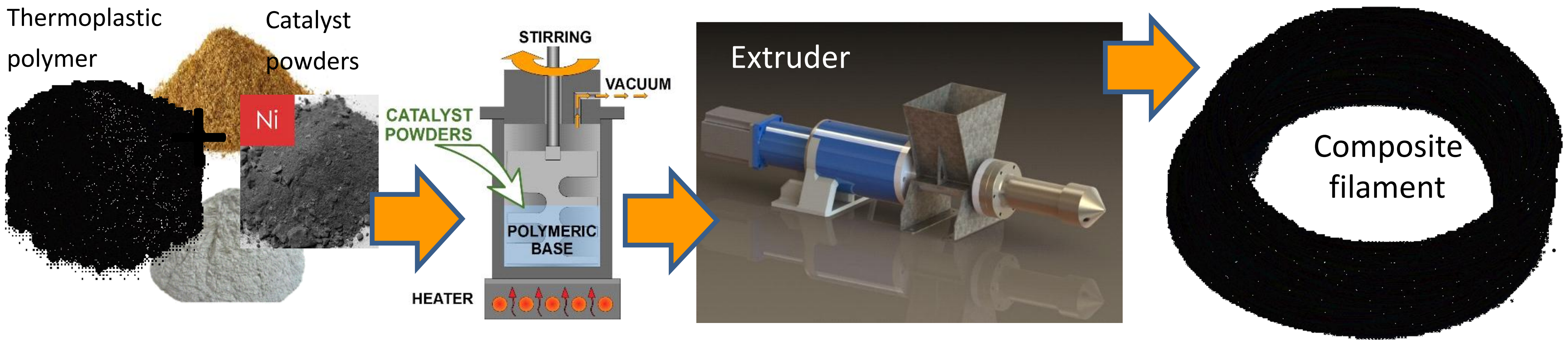
Haj Ibrahim S., Neumann M., Klingner F., Schmidt V., Wejrzanowski T., Materials and Design 133 (2017)

Syntectic fuels
The concept

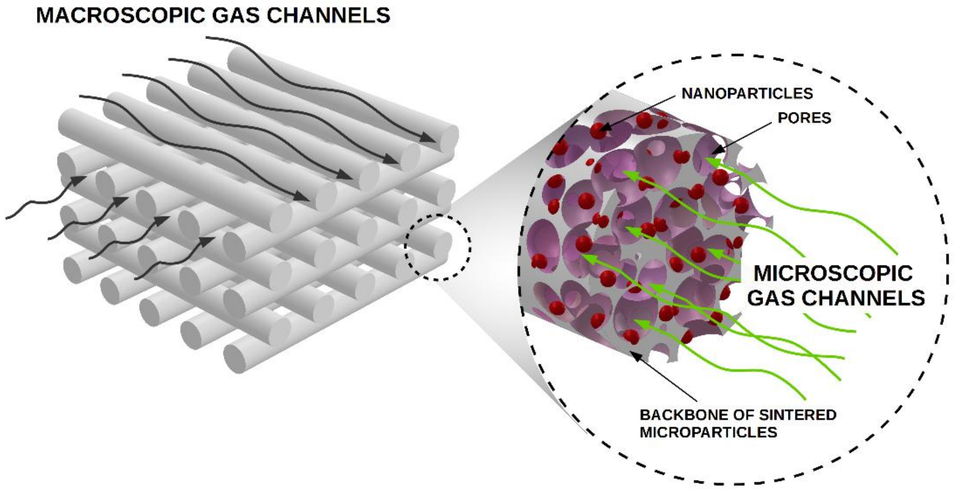


DOI: 10.3390/en11020392

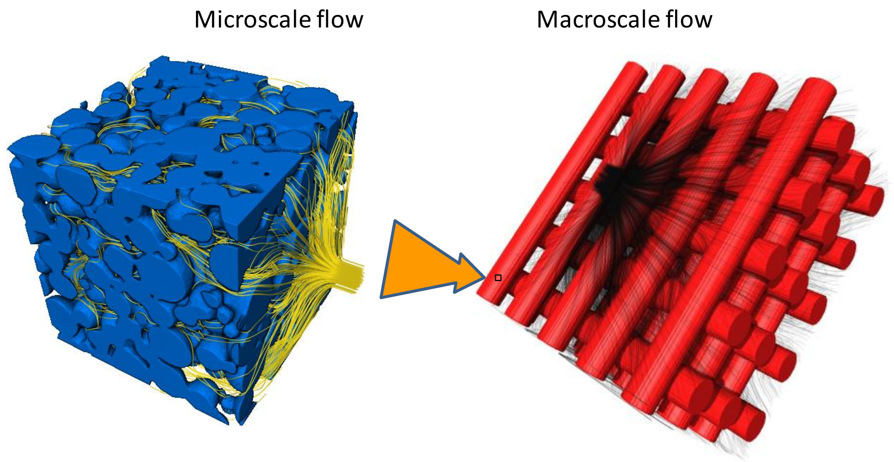
Hierarchical porous materials – 3D printing
The concept



Fabrication of hierarchical open porous materials by application of 3D printing

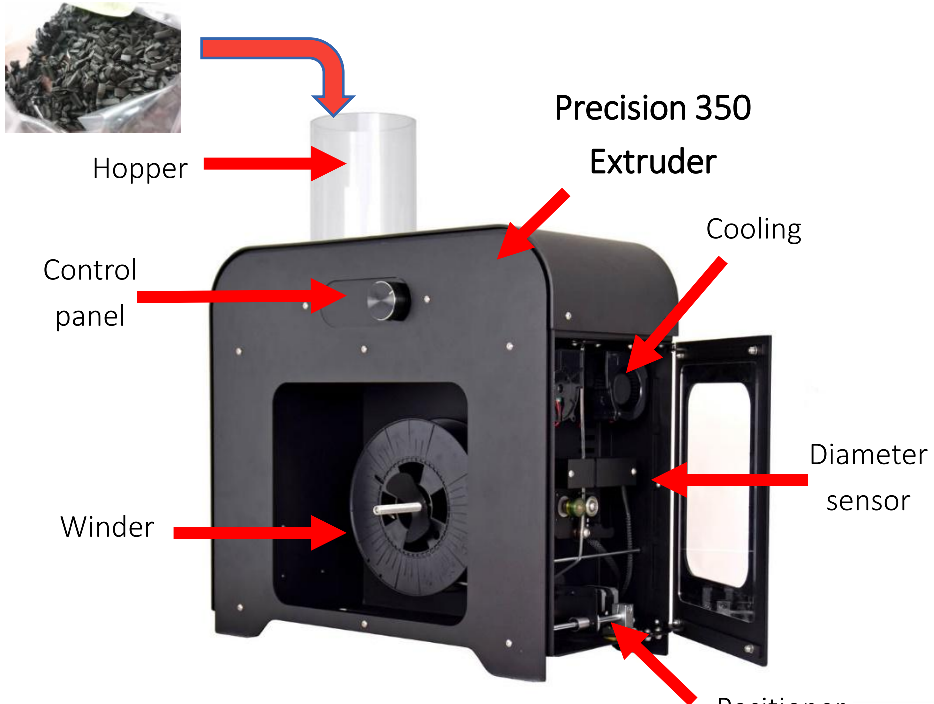


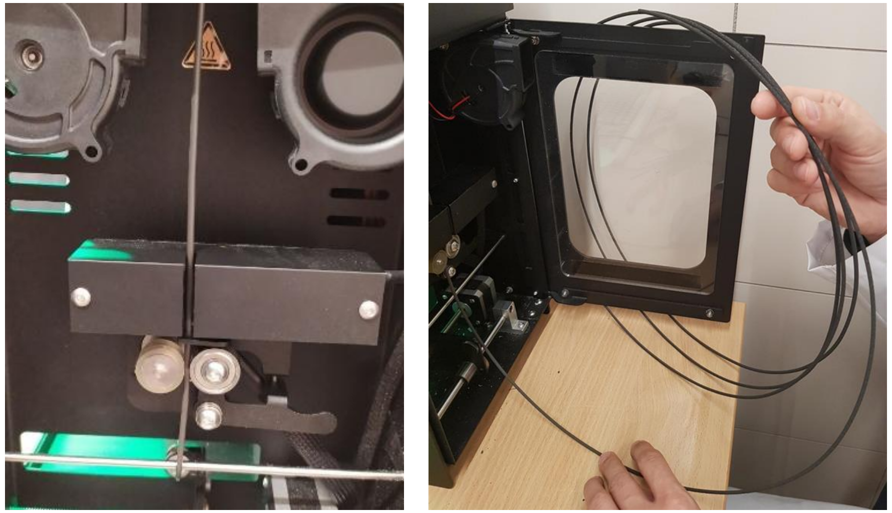
Schematic illustration of hierarchical open-porous microstructure of catalytic materials fabricated via 3D printing



Multiscale modeling of reactive flow in hierarchical microstructure.

3D printing of hierarchical open-porous materials by FDM (Fused Deposition Modeling)

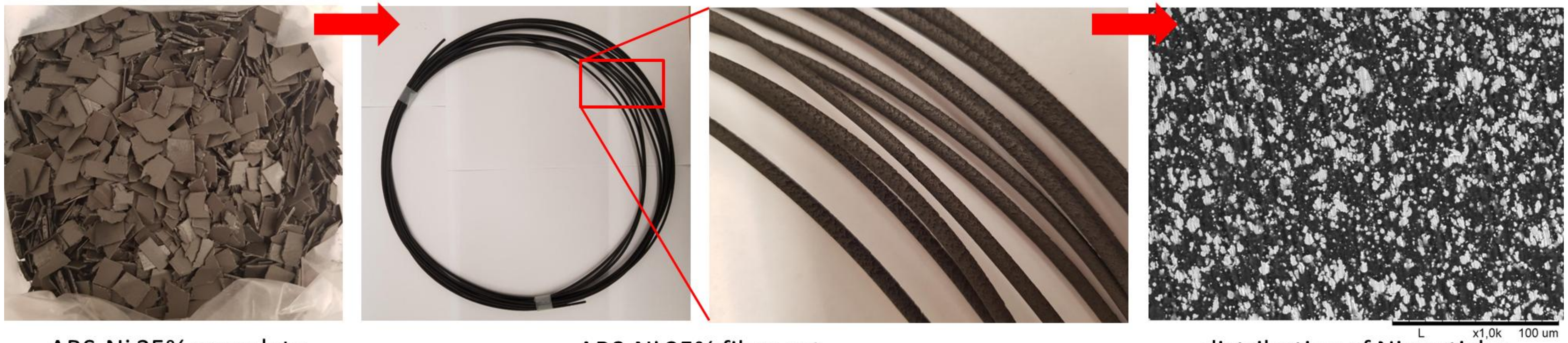




Filament diamater – 2,85 μm

Filament extrusion

SEM analysis



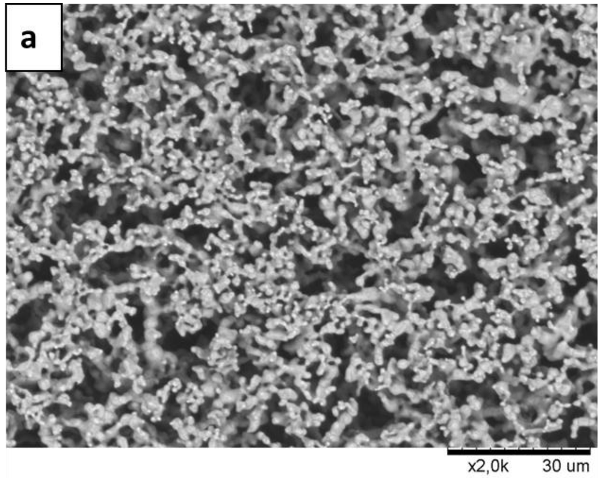
ABS-Ni 25% granulate

ABS-Ni 25% filament

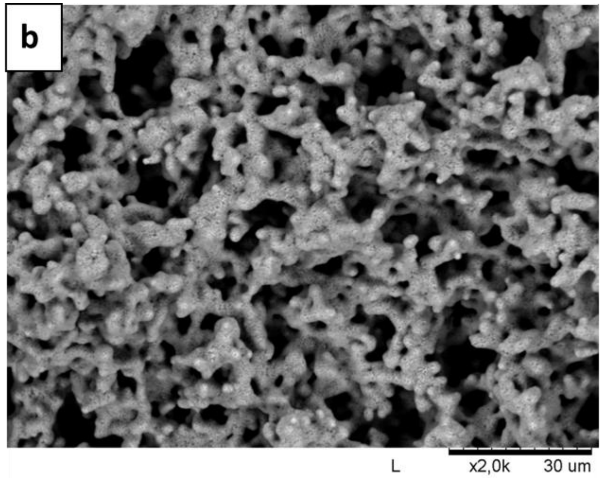
distribution of Ni particles

Porous structures in FDM 3D printing technology

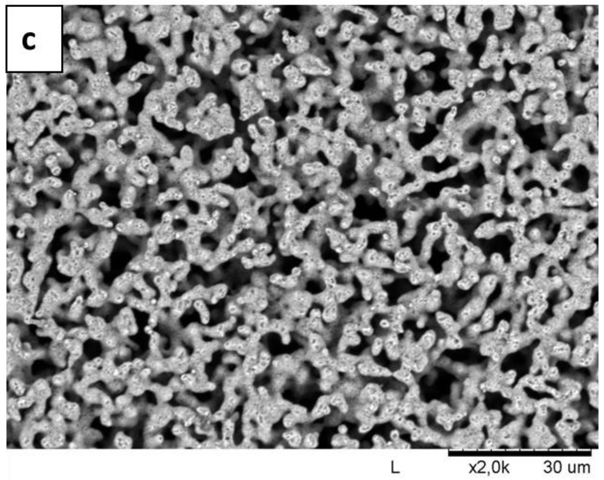
SEM images for prints after heat treatment:



PLA-Ni 5% on Ni faom (a)



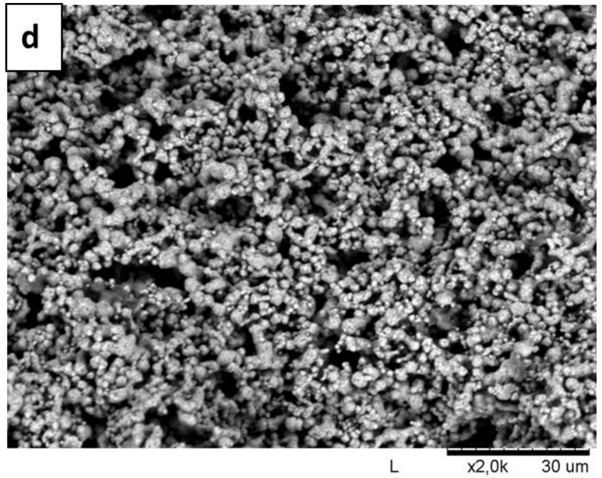
PVB-Ni 25% (b)



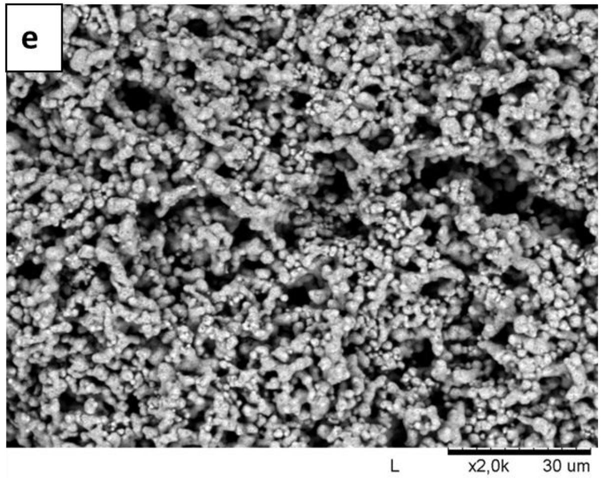
PVB-Ni 25% on Ni foam (c)

Uniform distribution of Ni particles in the composite -> **controlled porosity**

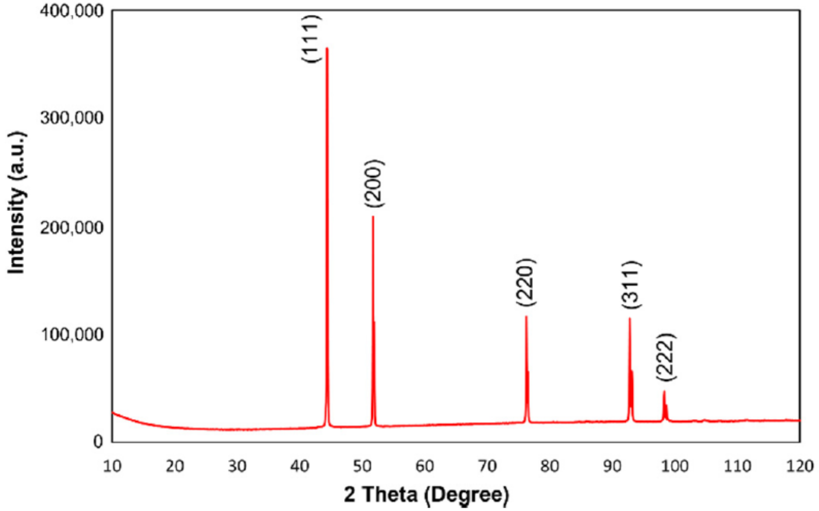
The produced materials are characterized by an **open pore structure**.



ABS-Ni 25% (d)



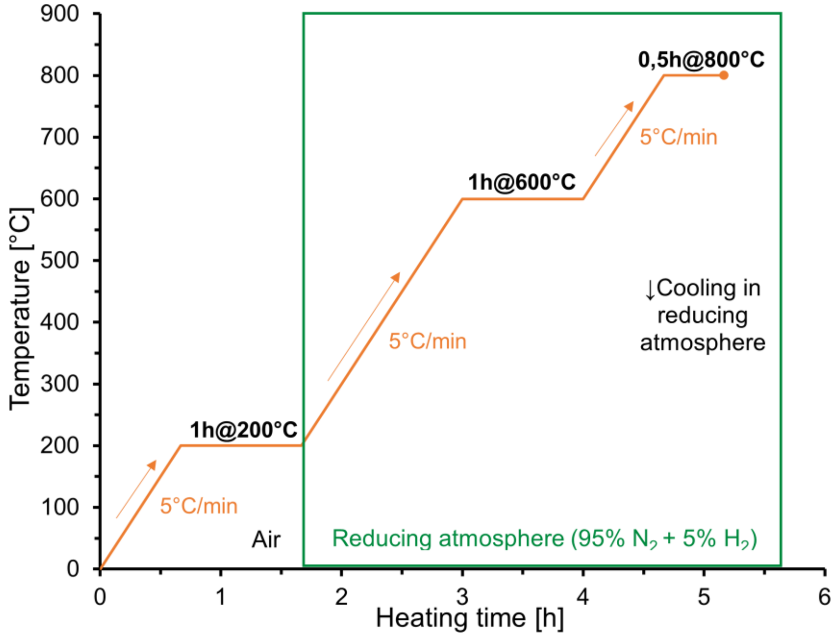
ABS-Ni 25% on Ni foam (e)



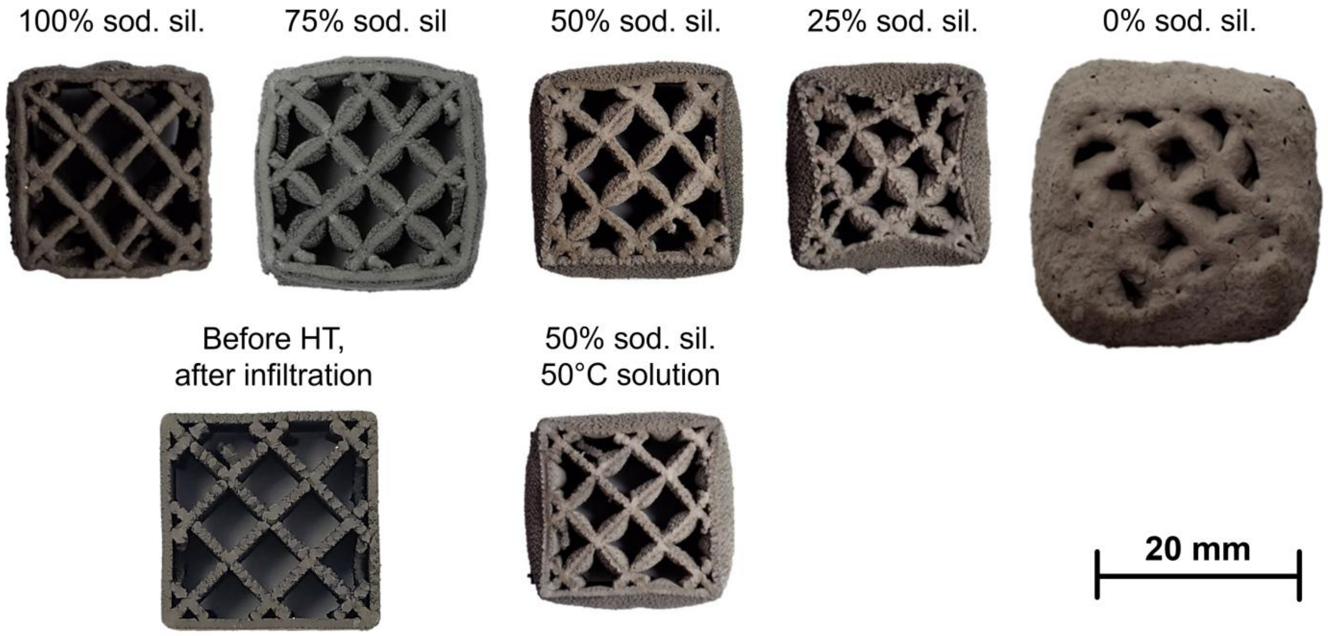
E. Mackiewicz, T. Wejrzanowski, B. Adamczyk-Cieślak, G.J. Oliver *„Polymer–Nickel Composite Filaments for 3D Printing of Open Porous Materials”,* Materials 2022, 15, 1360

Impregnation of 3D printed structures

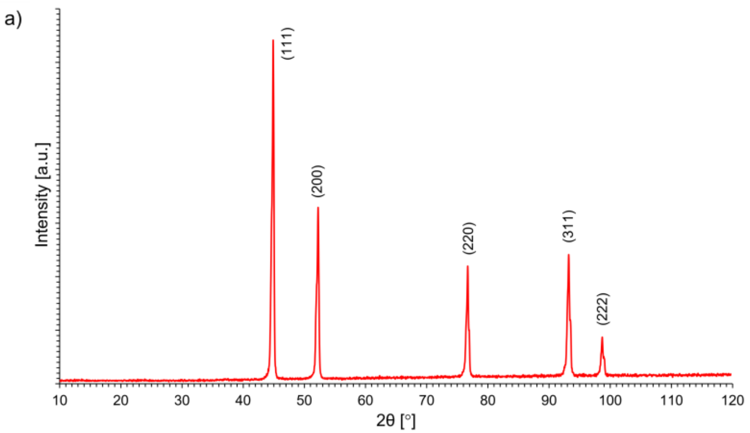
Heat treatment

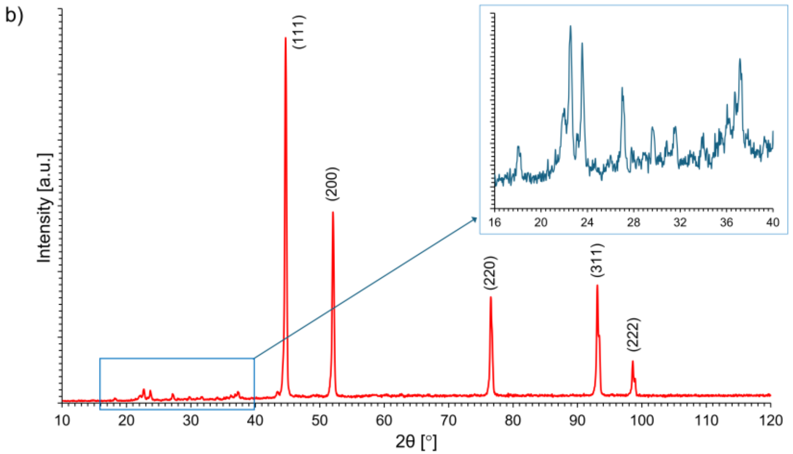


3D printed samples infiltrated by different sodium silicate solution concentrations



non-impregnated sample
(0% sod. silicate)

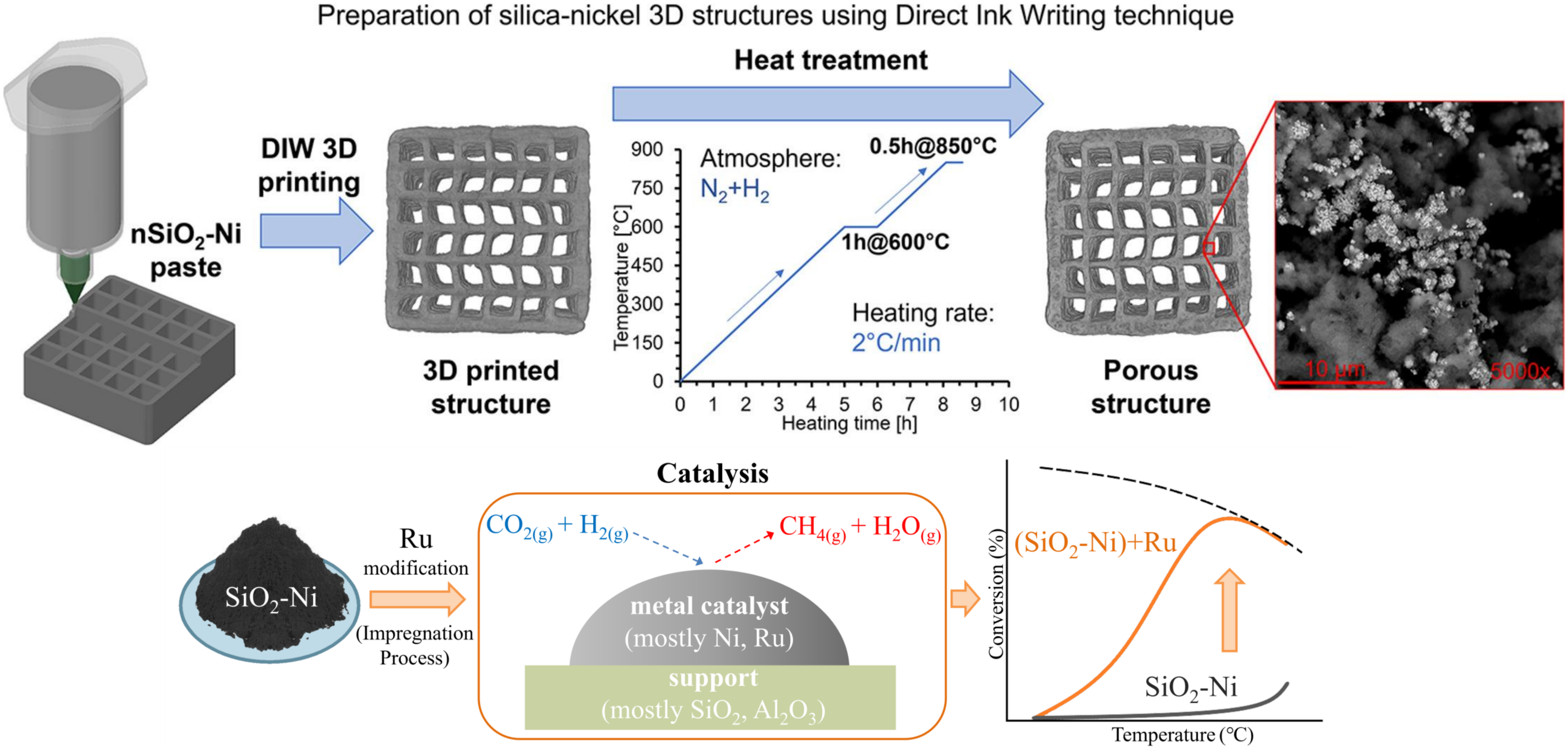




impregnated sample
(100% sod. sil.)

E. Mackiewicz, R. Nowacki, G. Komorowska, T. Wejrzanowski „*Impregnation of composite 3D prints obtained by material extrusion technology as an effective method of preserving the spatial geometry of the material*”, *International Journal of Precision Engineering and Manufacturing-Green Technology* 2025 (under review)

Porous 3D printed materials – Direct Ink Writing (DIW)



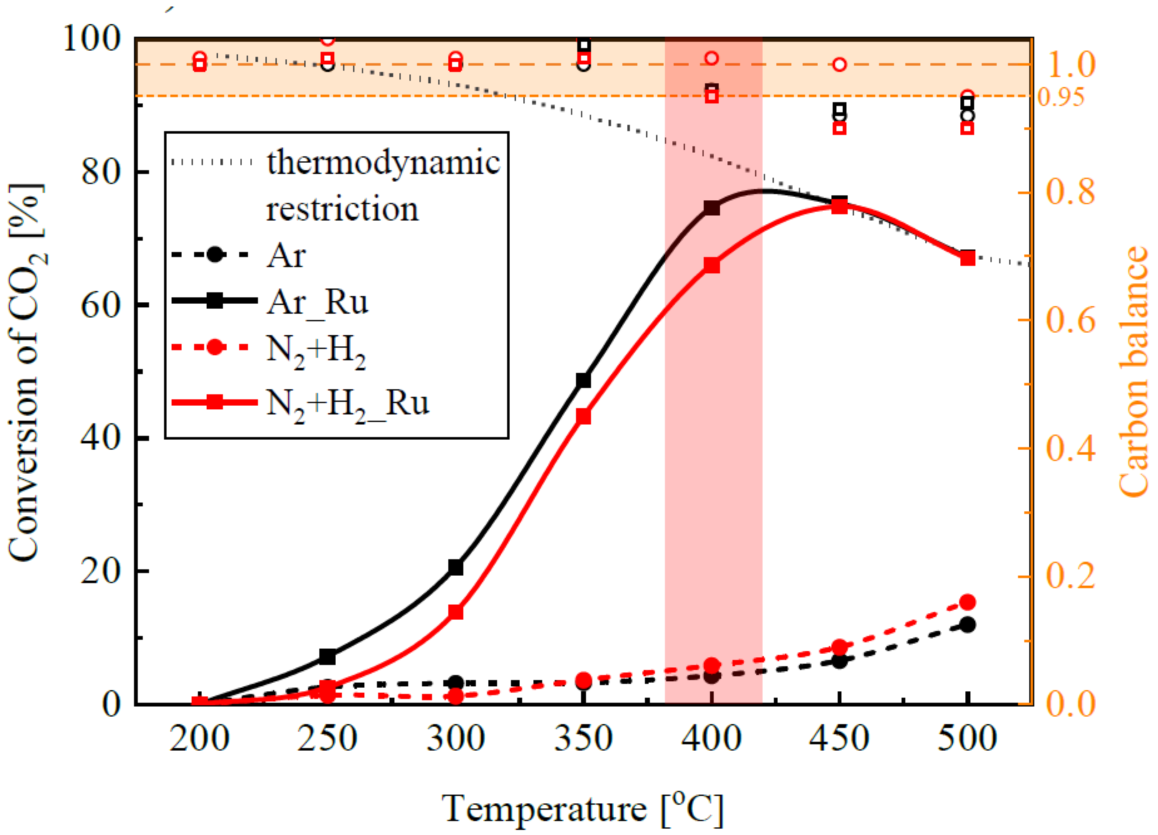
Mackiewicz, E., Wejrzanowski, T., Nowacki, R., Jaroszewicz, J., Marchewka, J., Wilk, Ł., Bezkosty, P., & Sitarz, M. (2023). 3D hierarchical porous structures printed from a silica-nickel composite paste. *Applied Materials Today*. https://doi.org/10.1016/j.apmt.2023.101859

R. Nowacki, E. Mackiewicz, G. Komorowska, T. Wejrzanowski, J. Marchewka, Ł. Wilk, M. Sitarz, M. Pietrowski, Exploring the Properties of DIW 3D Printed SiO2-Ni Structures Impregnated by Ruthenium: Influence of Sintering Atmosphere and Initial Tests for Catalytic Applications, 2025 (submitted)

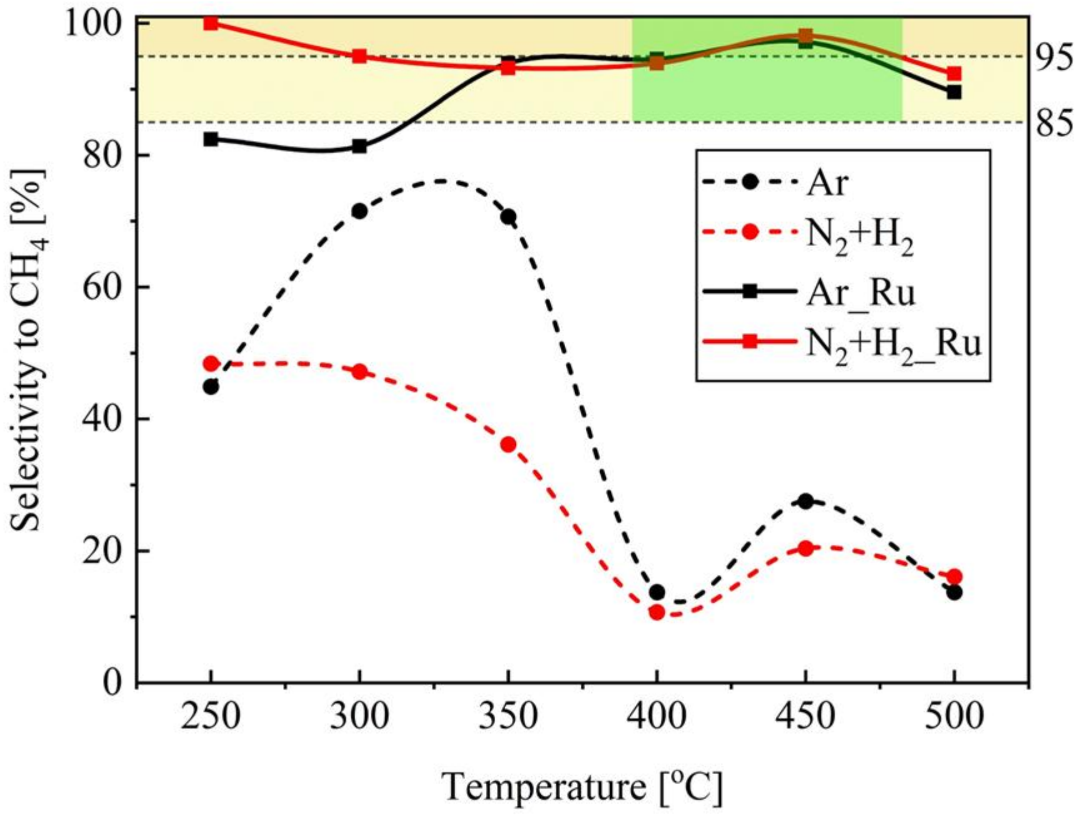
Porous 3D printed materials – Direct Ink Writing (DIW)

The catalytic activity tests for the Ni catalysts and Ru-promoted catalysts :

CO_2 conversion and carbon balance



selectivity to CH_4

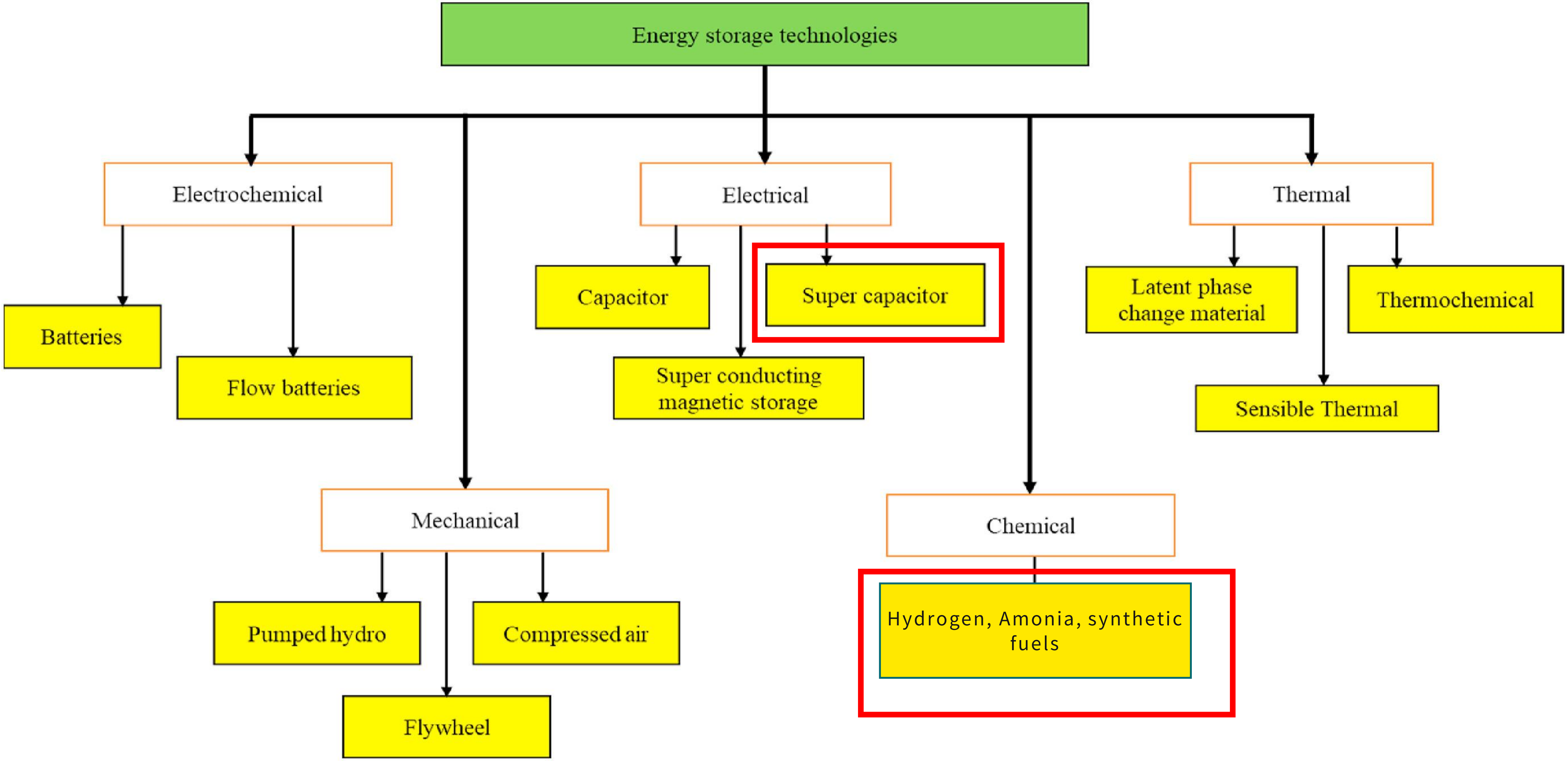


At 400 °C CO_2 conversion reached almost 75% and 66% for Ar_Ru and H_2+N_2_Ru, respectively

Monolithic catalysts - tests

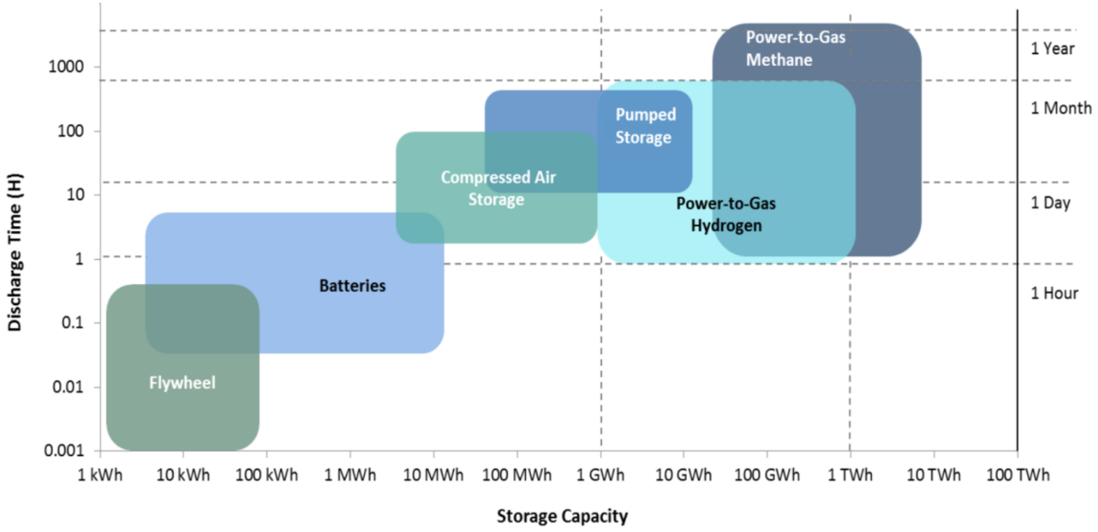
R. Nowacki, E. Mackiewicz, G. Komorowska, T. Wejrzanowski, J. Marchewka, Ł. Wilk, M. Sitarz, M. Pietrowski, Exploring the Properties of DIW 3D Printed SiO2-Ni Structures Impregnated by Ruthenium: Influence of Sintering Atmosphere and Initial Tests for Catalytic Applications, 2025 (submitted)

Storage of Energy - Technologies



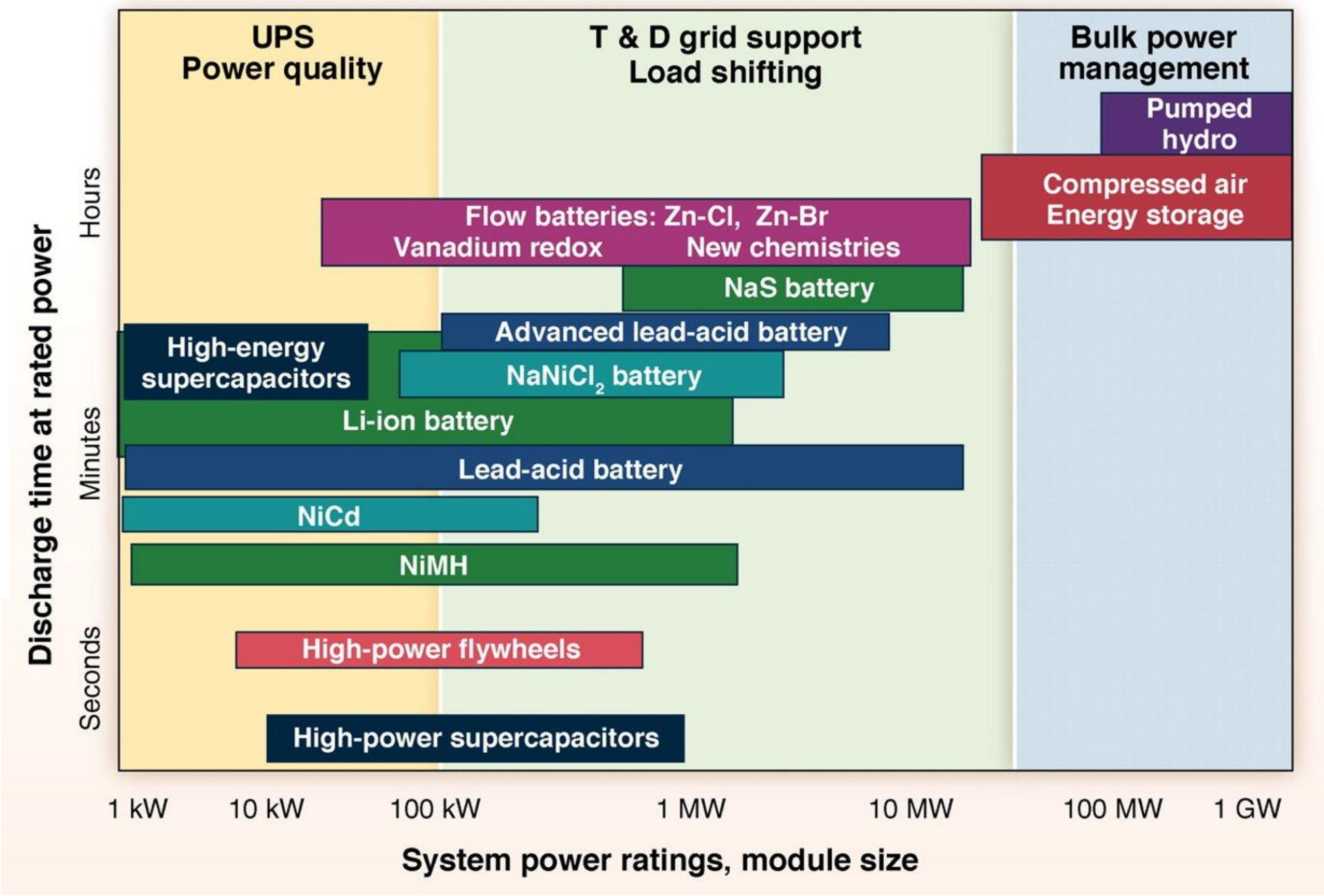
A.A. Kebede at al.., A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration, Renewable and Sustainable Energy Reviews, 159, 2022, 112213, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2022.112213.

Storage of Energy – Technologies



CALIFORNIA HYDROGEN BUSINESS COUNCIL

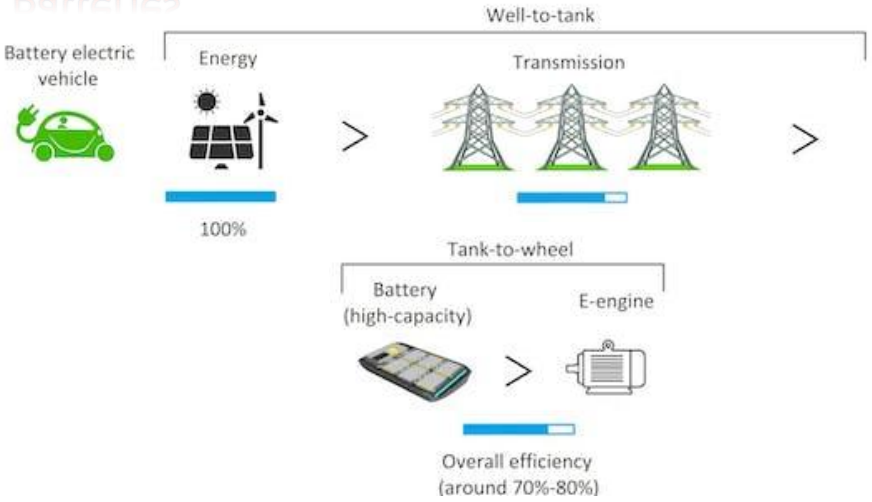
Power-to-Gas: The Case for Hydrogen White Paper



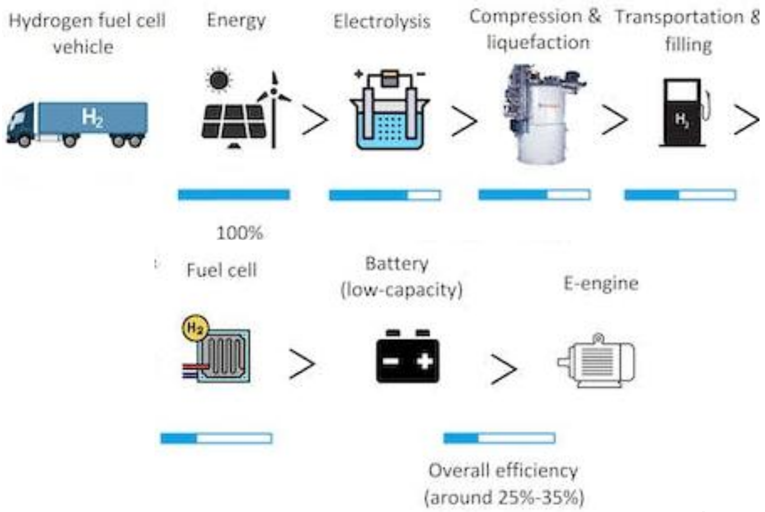
B. Dunn, at al., Electrical Energy Storage for the Grid: A Battery of Choices, Science 334, 6058 (2021), 928. DOI: 10.1126/science.1212741

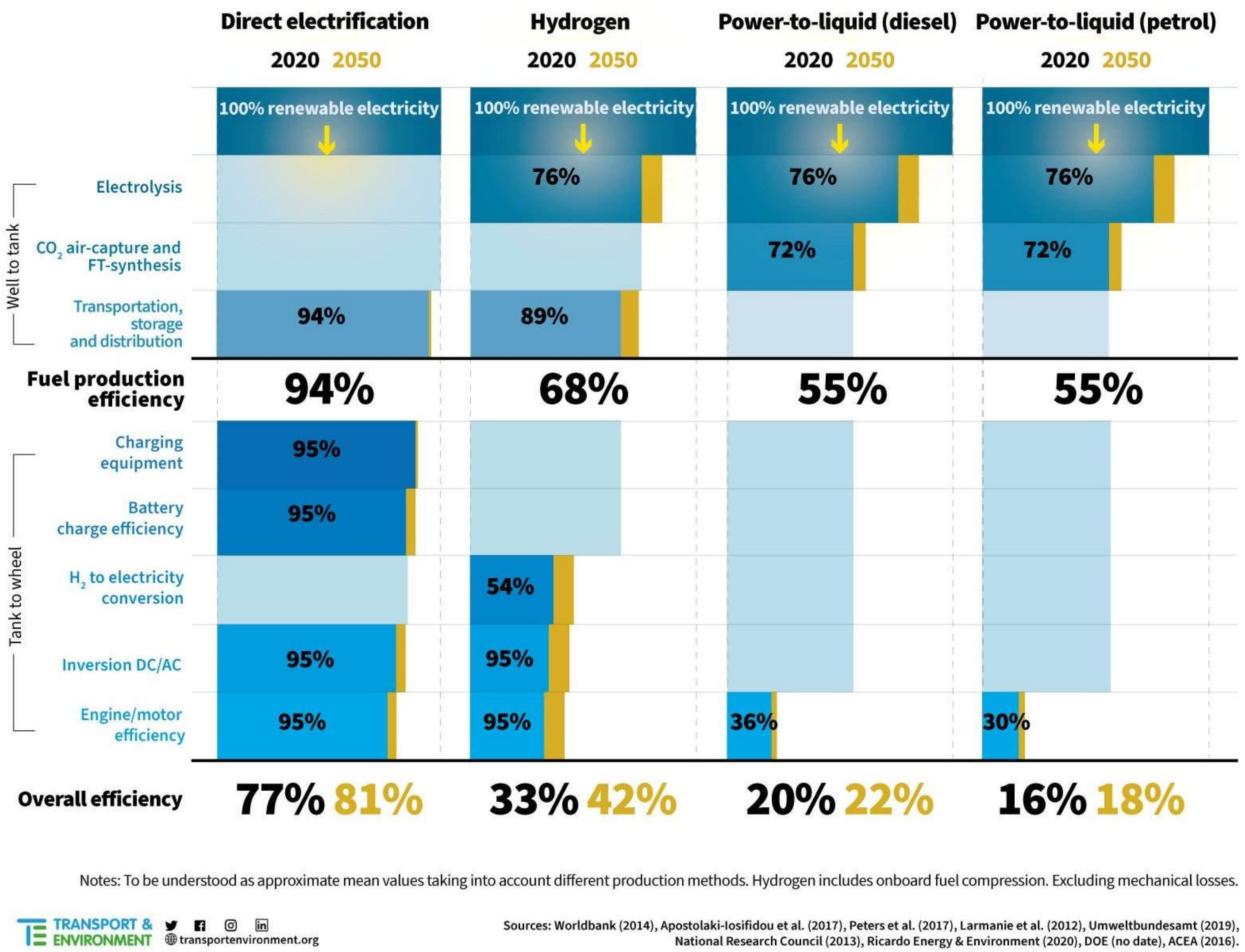
Hydrogen vs batteries

Batteries



Hydrogen





https://creativecommons.org/

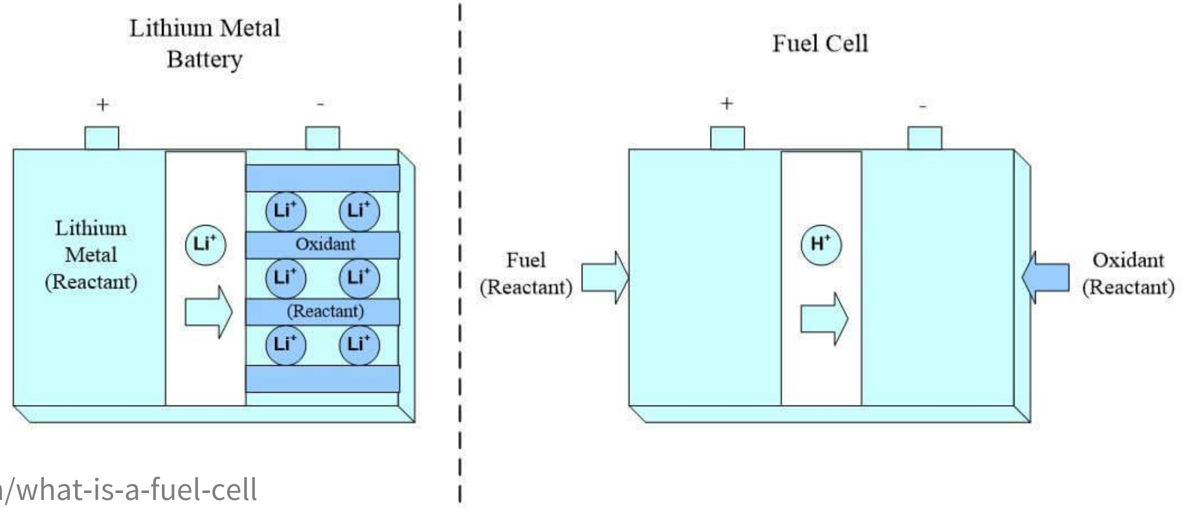
Hydrogen vs batteries

Batteries

- Energy density (0.5 kWh/l – 0.5 kWh/kg)
- Battery power density (>500 W/kg)
- Electrical efficiency (>90%)
- Durability (warranty – 10-15 years)
- Low charging speed
- Currently high battery purchase price
- Availability of raw materials (lithium, cobalt)
- High technological maturity

Hydrogen (fuel cells)

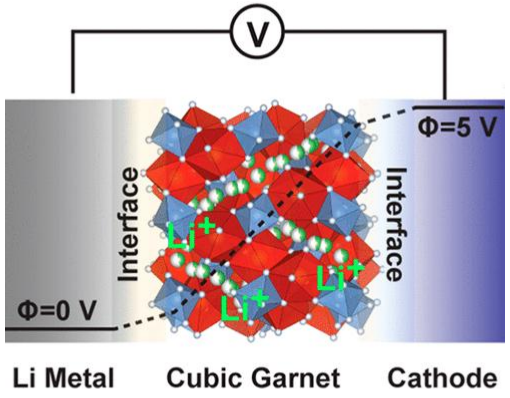
- Hydrogen energy density (30 MPa – 0.6 kWh/l – 33 kWh/kg)
- Fuel cell power density (<100 W/kg)
- Electrical efficiency (40-50%)
- Fuel cell durability (warranty – 6 years)
- High charging speed
- Currently high fuel cell purchase price
- Availability of raw materials (precious metals)
- Medium technological maturity



https://www.fuelcellstore.com/blog-section/what-is-a-fuel-cell

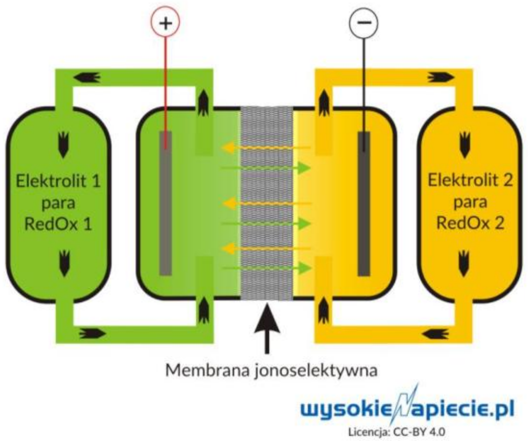
Emerging new battery technologies

Solid State Batteries



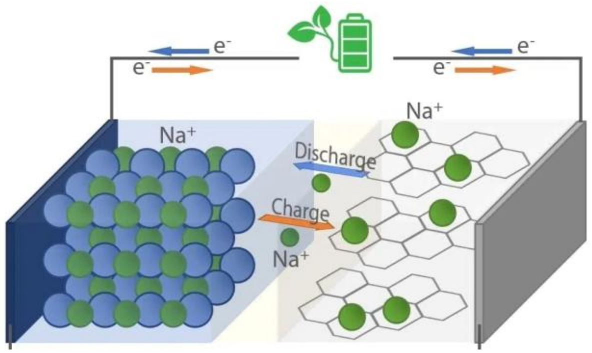
Garnet-Type Solid-State Electrolytes: Materials, Interfaces, and Batteries Chengwei Wang et al. *Chemical Reviews* **2020** *120* (10), 4257-4300 DOI: 10.1021/acs.chemrev.9b00427

Flow Batteries



https://wysokienapiecie.pl/1254-brakujace-ogniwo-energetyki/

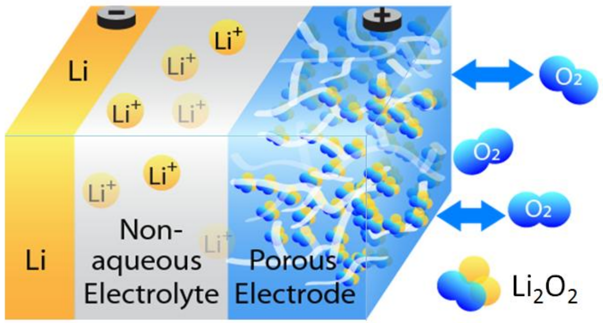
Na-ion Batteries



Katoda Elektrolit Anoda

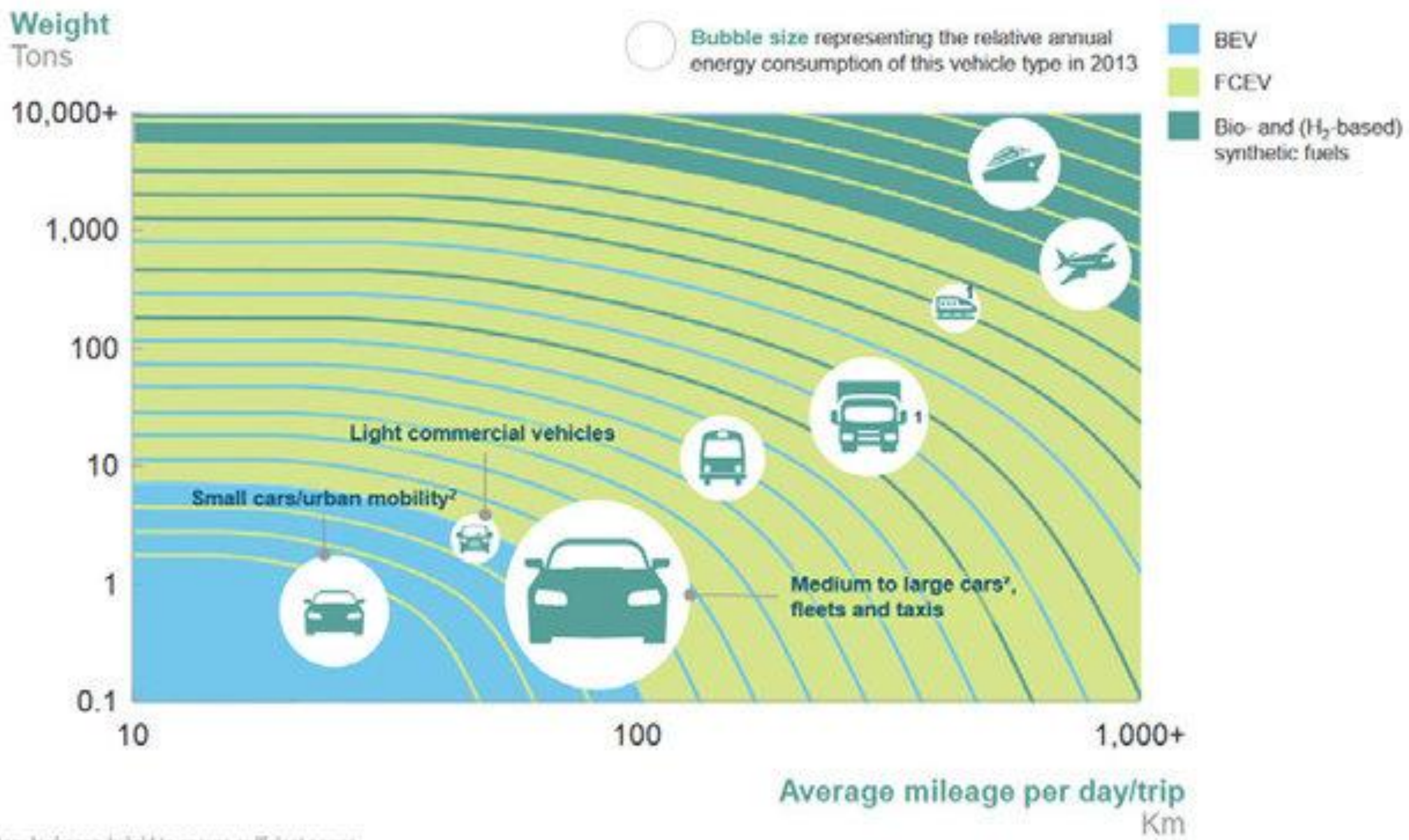
https://www.azom.com/article.aspx?ArticleID=22278

Li/Na-air Batteries



https://debuglies.com/2018/07/24/new-problem-with-lithium-oxygen-batteries/

Hydrogen or/and batteries ?



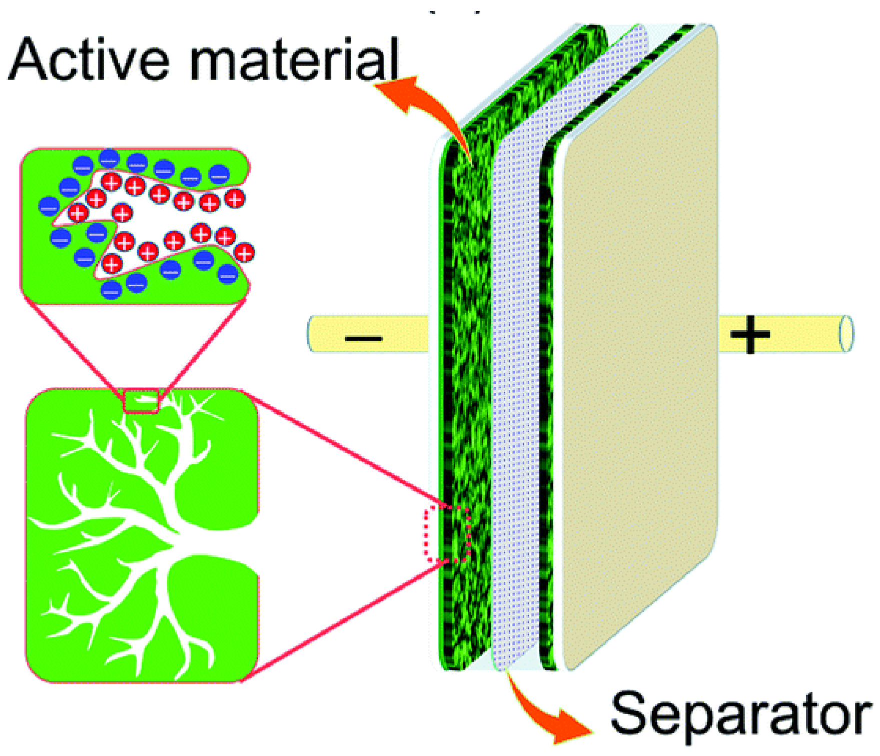
1 Battery-hydrogen hybrid to ensure sufficient power
2 Split in A- and B-segment LDVs (small cars) and C+-segment LDVs (medium to large cars) based on a 30% market share of A/B-segment cars and a 50% less energy demand

Source: Toyota, Hyundai, Daimler

Maybe something else? Supercapacitors

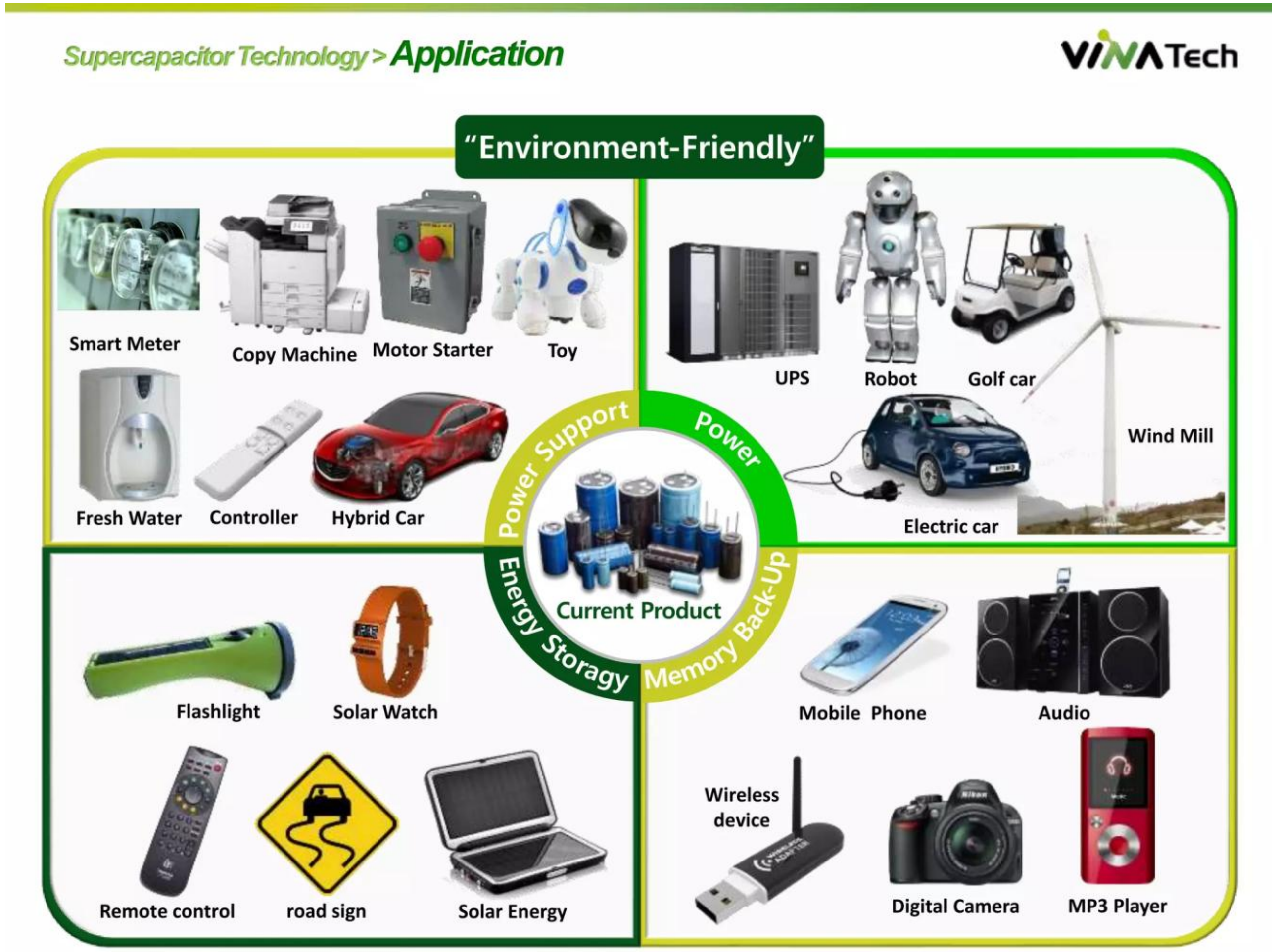
Supercapacitor: An advanced energy storage device.

- **High power density (higher than batteries)**
- **Wide operating temperature range**
- **Long cycle life (over 10 years)**
- **Fast Charging**
- **Less weight**
- **Low cost**



Typical construction of supercapacitor devices

Applications of supercapacitor devices



Trams in Germany powered by supercapacitors use 30% less energy than their equivalents in other regions.

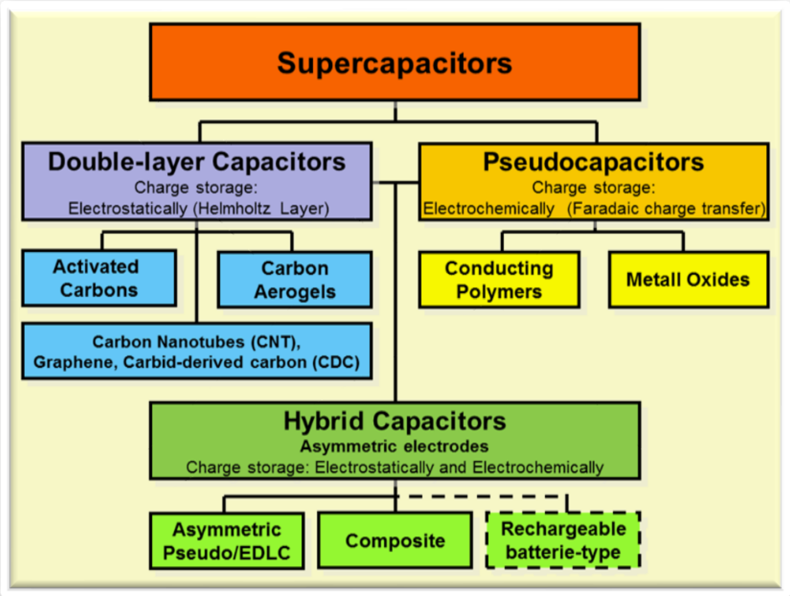
Ref: Supercapacitors take charge in Germany By Philip Ball Feature Editor Yury Gogotsi03, (2012)

Types and Classification of Supercapacitor

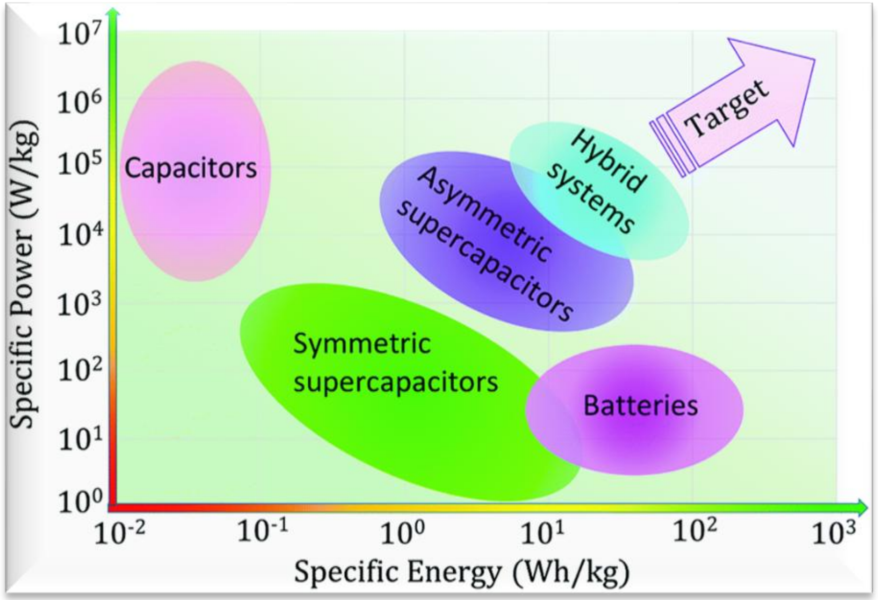
Objectives

A novel route for binder-free fabrication of porous electrodes

- Microwave-assisted hydrothermal method
- Fast and energy efficient
- Processing time few minutes
- Synthesis of various metallic/carbon compounds
- Novel porous nano architectures
- High surface area
- High electrochemical activity



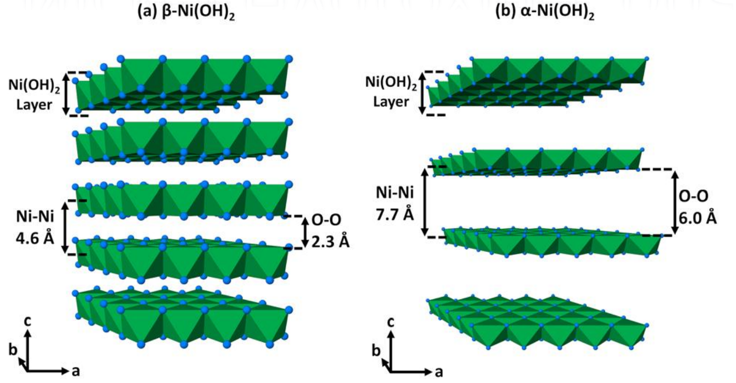
Types of supercapacitor devices



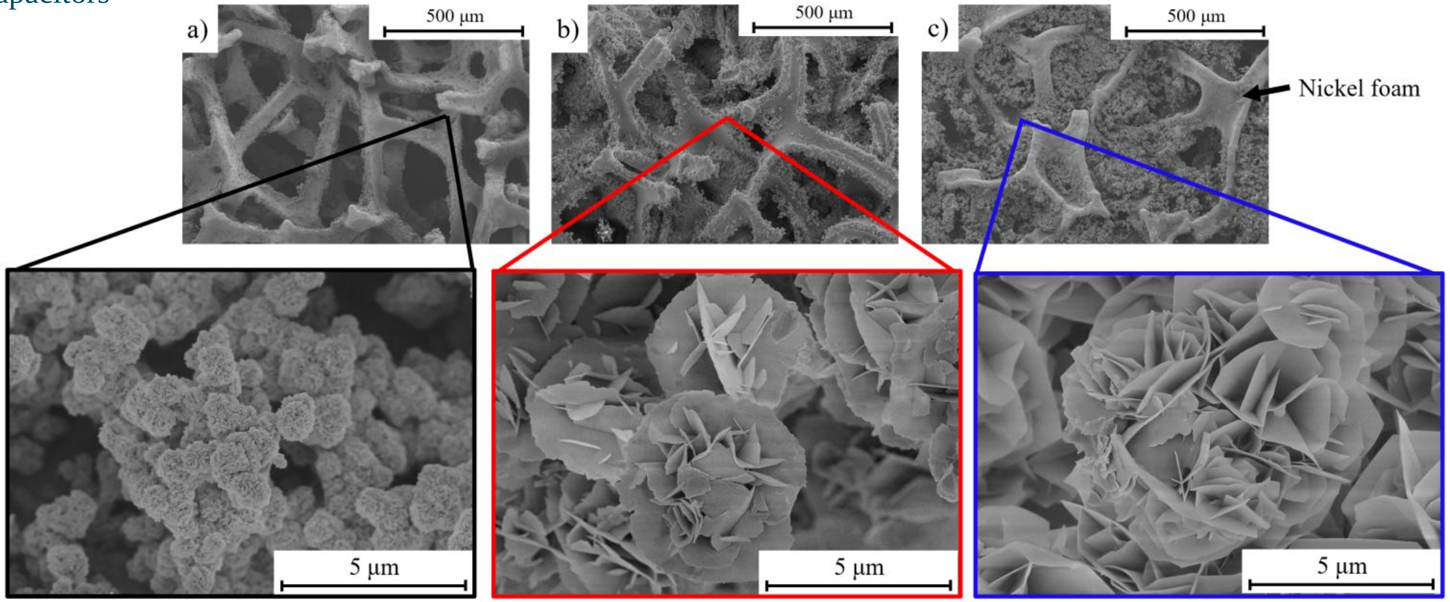
Ragone plot showing the specific power vs. specific energy of various energy storage devices.

Towards establishing standard performance metrics for batteries, supercapacitors and beyond DOI: 10.1039/c8cs00581h. Chem. Soc. Rev., 2019, 48, 1272

Nickel Hydroxide phases and electrochemical characteristics



Microwave-assisted hydrothermal synthesis of αβ-Ni(OH)$_2$ nanoflowers on nickel foam for ultra-stable electrodes of supercapacitors



β-Ni(OH)$_2$

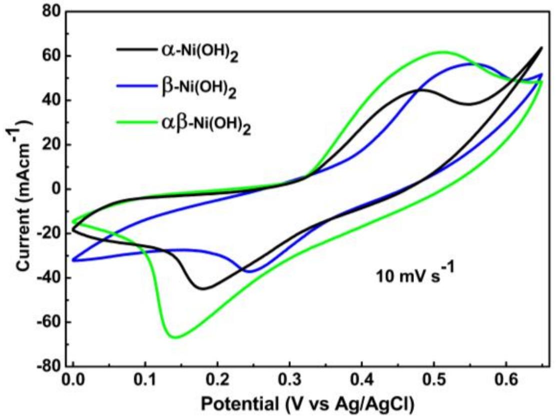
- **Capacitance** X
- **Cyclic stability** √

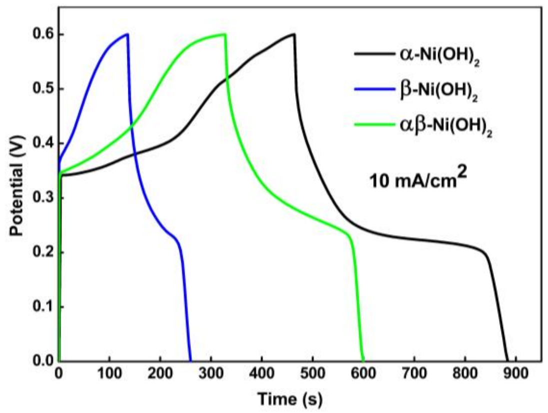
α-Ni(OH)$_2$

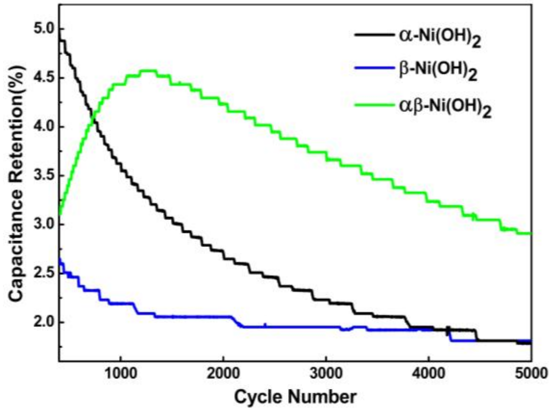
- **Capacitance** √
- **Cycle stability** X

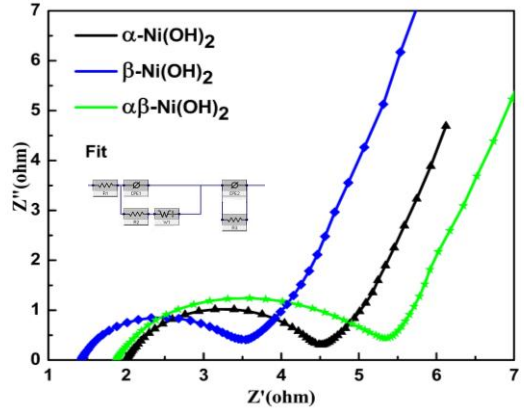
(a) α-Ni(OH)$_2$ **(b) β-Ni(OH)$_2$** **(c) αβ-Ni(OH)$_2$**

Determination of layered nickel hydroxide phases in materials disordered by stacking faults and Interstratification Mater. Chem. A, 2023, 11,789



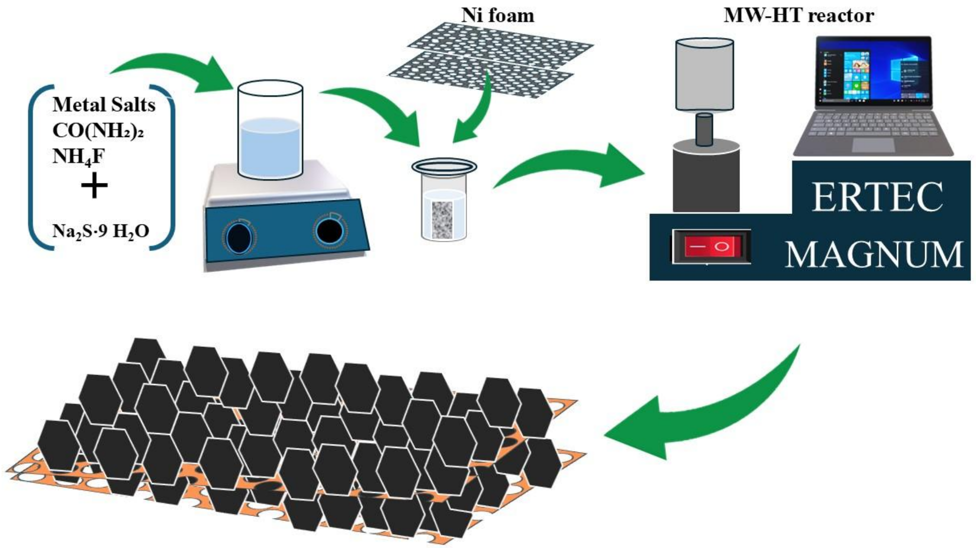


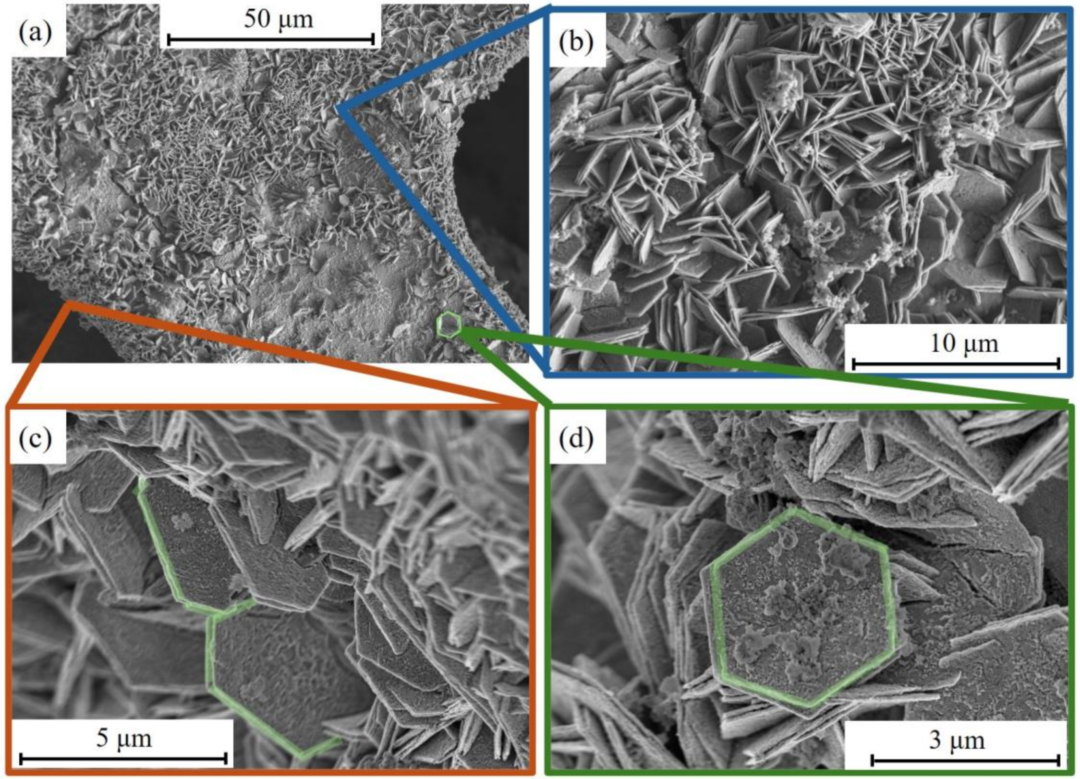




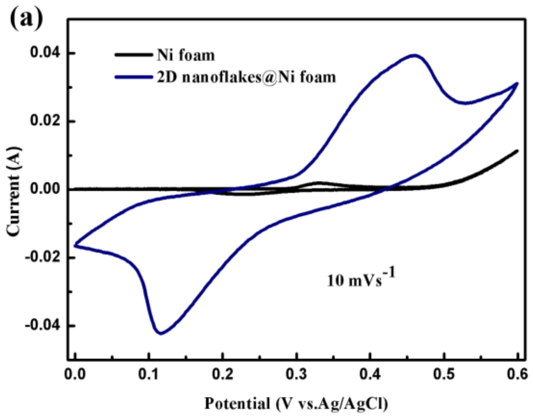
Muhammad Saleem Akhtar, Tomasz Wejrzanowski et al. Microwave-assisted hydrothermal synthesis of αβ-Ni(OH)2 nanoflowers on nickel foam for ultra-stable electrodes of supercapacitors https://doi.org/10.1016/j.electacta.2024.145284

Novel 2D hexagonal nanoflakes Cerium/Nickel Sulfide in situ grown on nickel foam - Anode

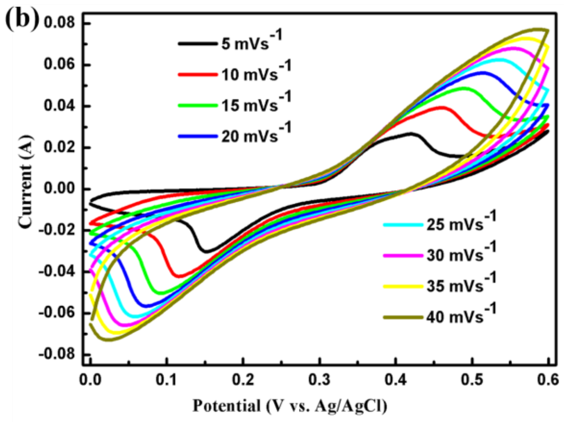




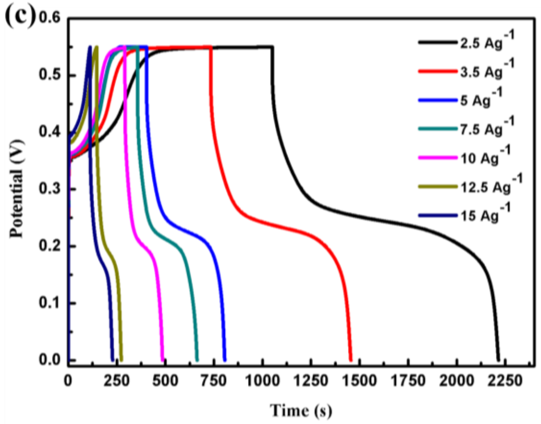
Comparative CV curves of bare Ni foam and 2D nanoflakes @ Ni foam



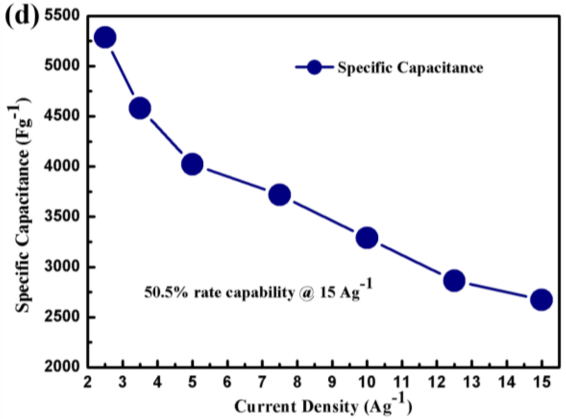
CV curves of 2D nanoflakes @ Ni foam at different scan rates



Exceptional performance due to its 2D morphology, achieving a **high capacitance** of 5286 Fg^{-1} with an **high energy density** of approximately 222.09 Wh/kg and a power density of 687.19 W/kg at a current density of 2.5 Ag^{-1}



GCD curves of 2D nanoflakes @ Ni foam

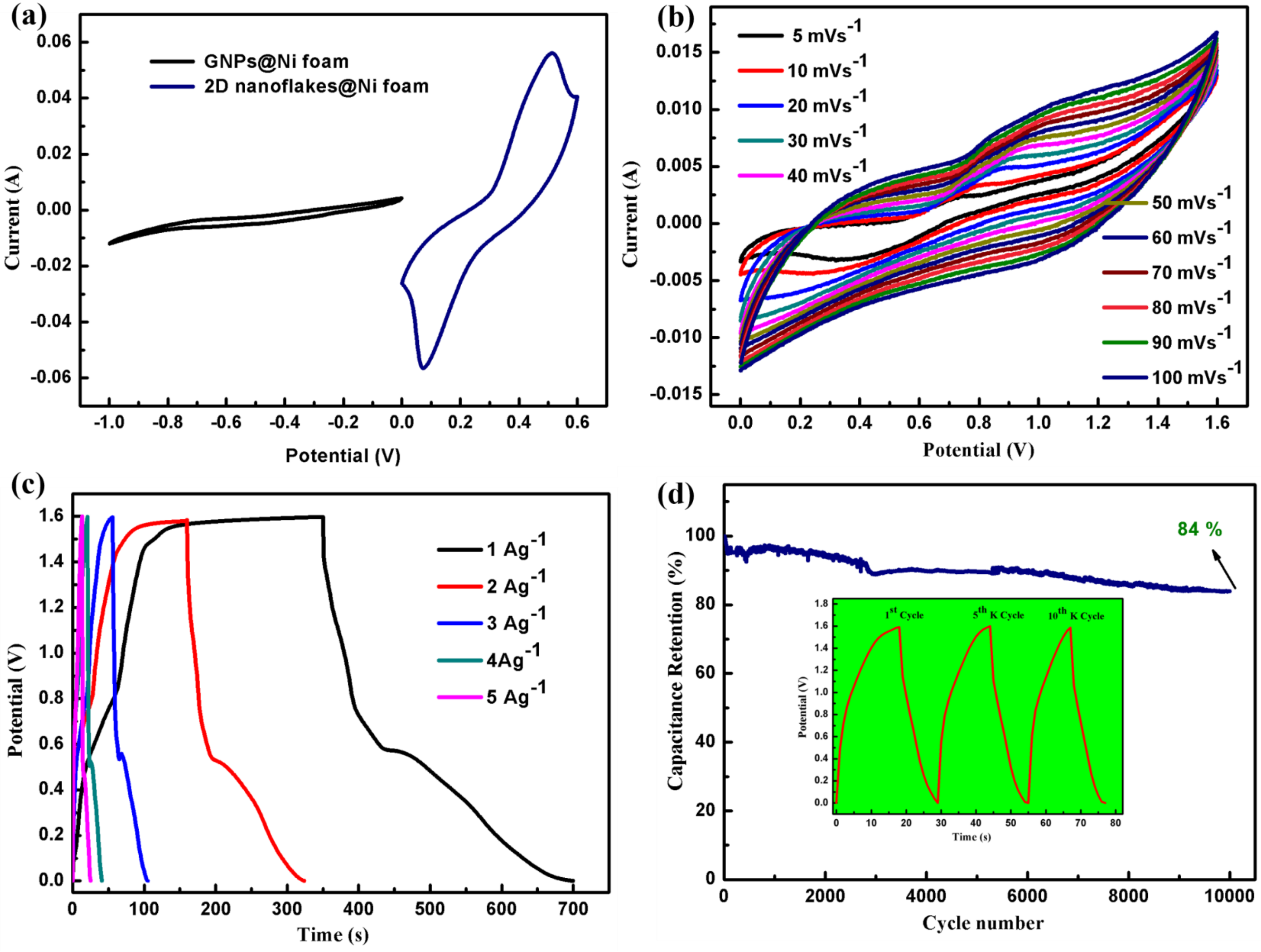


GCD curves of 2D nanoflakes @ Ni foam (d) capacitance vs. discharge current density

Novel 2D hexagonal nanoflakes Cerium/Nickel Sulfide anode + GNP cathode

GNP – Graphene nano-pellets

The device - Full asymmetric cell



The 2D nanoflakes @Ni foam//GNPs @Ni foam asymmetric supercapacitor exhibited an **high energy density** of 77.51 Wh/kg and a power density of 797.25 W/kg at a current density of 1 Ag^{-1}. Furthermore, the asymmetric device demonstrated **exceptional cyclic performance, retaining approximately 84% of its initial capacitance after 10,000 continuous charging/discharging cycles**

(a) CV curves of positive and negative electrodes (b) CV curves of 2D nanoflakes @Ni foam//GNPs@Ni foam (c) GCD curves of 2D nanoflakes @Ni foam//GNPs@Ni foam at different current densities (d) Cyclic performance of asymmetric supercapacitor

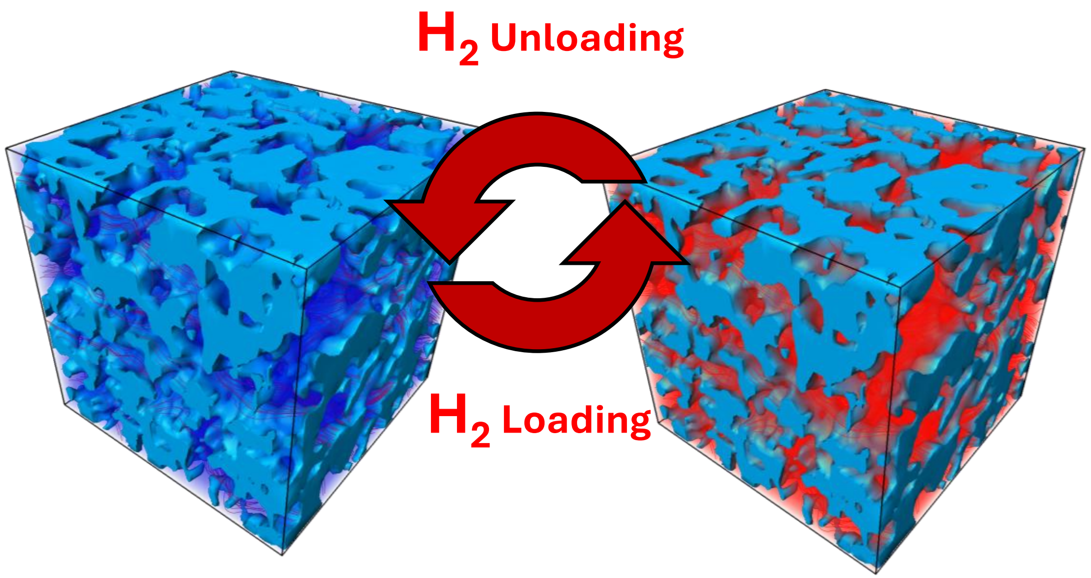
To be published

Hydrogen storage – new concepts

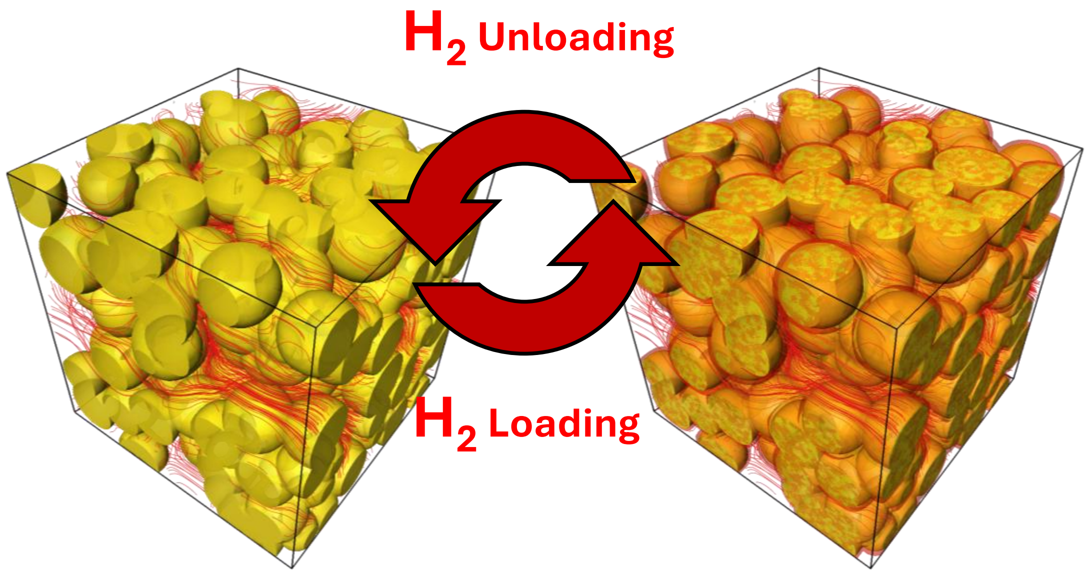
NEW PROJECT:
Cost- and resource-efficient storage of hydrogen at ambient temperature and at a maximum pressure of 3.5 MPa, NCDR, European, 2024-2027

Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT | Germany
AMAZEMET | Poland
JA-Gastechnology GmbH | Germany
VSB-Technical University of Ostrava, CEET; Energy Research center | Czech Republic
Faculty of Sciences of Monastir, University of Monastir | Tunisia
Warsaw University of Technology | Poland
Institut für Nichtklassische Chemie e.V. | Germany
Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. | Germany

Aerogel H_2 storage



HEA H_2 storage



Recent projects

NCBR
National Centre for Research and Development

1. High-performance molten carbonate fuel cells (MCFC), 2015-2018, PBS, NCRD
2. Innovative matrix materials for molten carbonate fuel cells (MATRIX), 2016-2019, Poland-Taiwan bilateral project, NCRD
3. Improved fabrication of fuel cells for extended durability, improvement of working parameters, in particular power per volume/mass unit of the fuel cell and reduction of investment and exploitation costs by application of alternative catalytic systems in printing technology (AUGUSTINE), 2016-2019, POIR.01.02.00-00-0045/16, NCRD
4. Development of technology for noble metals and rare earth elements recycling for fabrication of molten carbonate fuel cell elements (RECREATE), 2017-2020, POIR. 01.02.00-00-0086/17-00, NCRD
5. Novel molten carbonate/ceramic composite materials for sustainable energy technologies with CO_2 capture and utilization (MOCO3), M-ERA_NET2/2016/04/2017, 2017-2020, NCRD
6. Development of the industrial scale of molten carbonate fuel cells and solid oxide electrolysers for integration into power-to-gas installations (TENNESSEE), 2018-2020, POIR, NCRD
7. Cost- and resource-efficient storage of hydrogen at ambient temperature and at a maximum pressure of 3.5 MPa, NCDR, European, 2024-2027

National Science Centre Poland

UCZELNIA BADAWCZA
INICJATYWA DOSKONAŁOŚCI

1. Study of the influence of microstructure and chemical composition on catalytic properties of open-porous components of molten carbonate fuel cells, 2018-2021, OPUS, NSC
2. Study of the influence of microstructure on reactive flow process in open-porous components for high-temperature fuel cells, 2018-2021, PRELUDIUM, NSC
3. POB Technologie Materiałowe of Warsaw University of Technology within the Excellence Initiative: Research University (IDUB) program
4. Hierarchical porous structures fabricated by 3D printing technology 2019-2024, OPUS, NSC
5. Carbonate-oxide fuel cell, 2023-2026, OPUS, NSC

International cooperation

Thank you !

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POLITECHNIKA WARSZAWSKA
WARSAW UNIVERSITY OF TECHNOLOGY