Paper Fuel Cells: Bringing the Hydrogen Economy to the Masses

Stephen M. Lyth

Platform of Inter/Transdisciplinary Energy Research (Q-PIT)

International Institute for Carbon Neutral Energy Research (I2CNER)

Energy 2050, Department of Mechanical Engineering, University of Sheffield, UK

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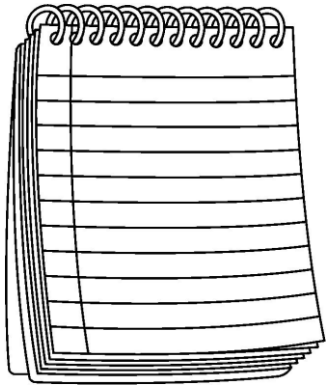
Elevator Pitch



Fossil Fuels

- CO_2 emissions lead to rising sea levels & extreme weather.
- PM2.5 emissions severely affect the **health** of the population.

Hydrogen Fuel Cells

- Hydrogen is a promising alternative to fossil fuels.
- It used in fuel cells to generate power with high efficiency.

Expensive Technology

- Fuel cells are too expensive for the average consumer.
- Partly due to the Nafion ionomer membrane.

Replace Nafion with "Paper"

- Nanocellulose is cheap, abundant, & biodegradable.
- Substituting Nafion with cellulose will reduce the cost of fuel cells.

My Background

Durham University: 1999-2003

- MSci in Physics
- Top 100 Global University (THE/QS)
- Top 5 in the UK (Guardian)
- Top physics department in UK (2003)
- Thesis project sponsored by Sony

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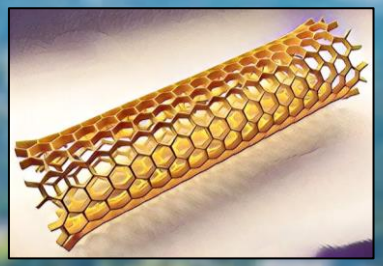
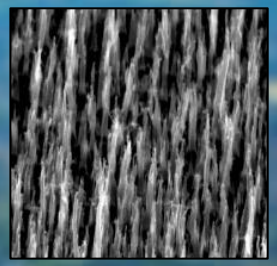
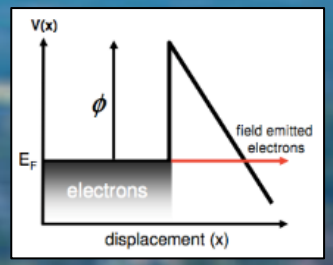
University of Surrey: 2004-2007

UNIVERSITY OF SURREY



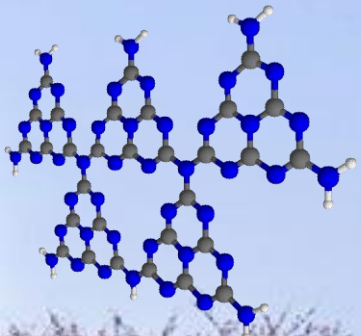


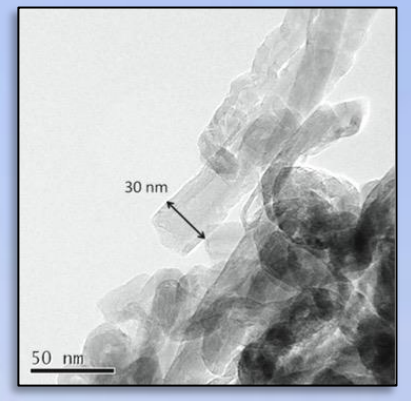


- PhD in Electrical and Electronic Engineering
- Top 10 University in UK (Guardian)
- Top 3 Engineering Department in UK (Guardian)

Tokyo Institute of Technology 2008-2011

東京工業大学
Tokyo Institute of Technology





- Postdoctoral Researcher
- Dept of Organic & Polymeric Materials
- Top 100 Global University (QS)
- Ranked 4th in Japan (THE)
- NEDO National Hydrogen Project

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Kyushu University: 2011-2022

- **Associate Professor**
- Platform of Inter / Transdisciplinary Energy Research (Q-PIT)
- International Institute for Carbon-Neutral Energy Research (I2CNER)
- **Global Ranking: 126 (QS)**

Leeds University: 2014-2016

- Visiting Assistant Professor
- Energy Research Institute
- Top 100 Global University (QS)

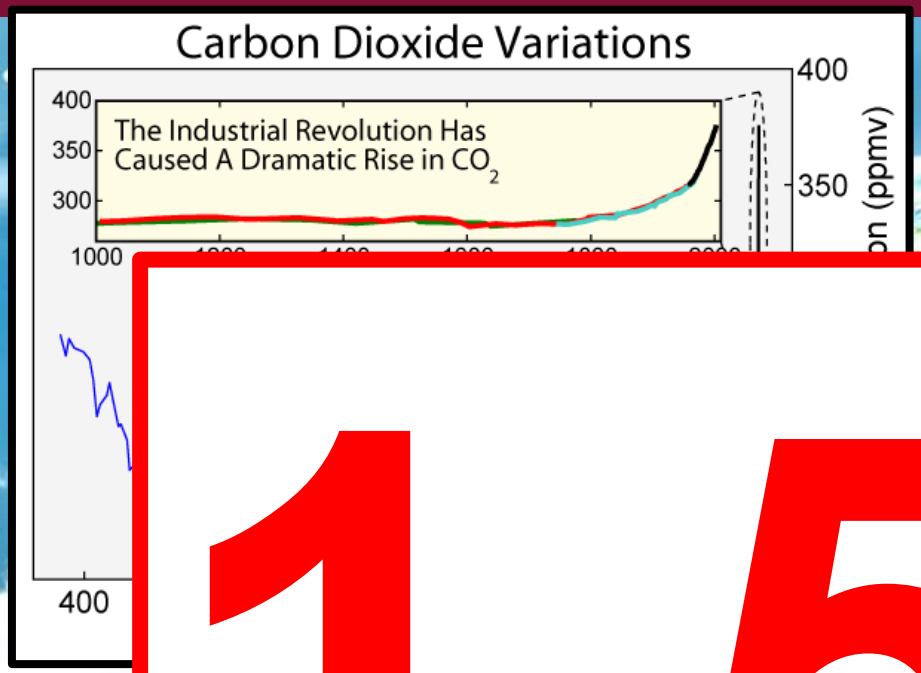
Sheffield University: 2015-

- Visiting Professor
- Energy 2050
- Global Ranking: 75 (QS)

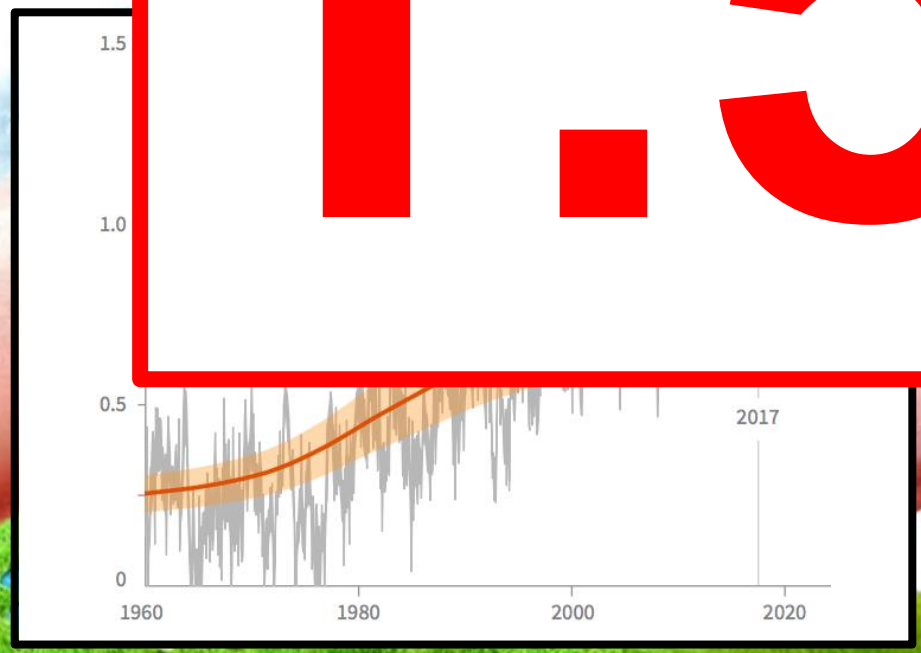

An tAontas Eorpach
European Union
ÉIRE
IRELAND
Pas
Passport

Motivation

Climate Change



1.5°C



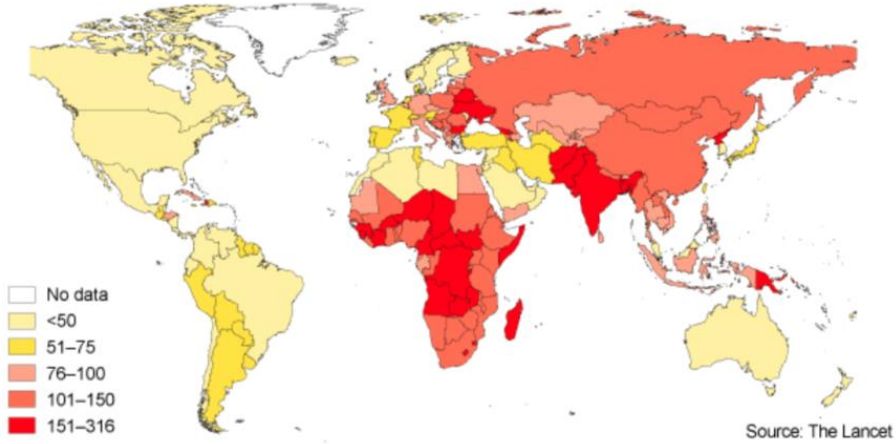
Pollution linked to one in six deaths

By Katie Silver
Health reporter, BBC News

20 October 2017 | Health | Share

Pollution has been linked to nine million deaths worldwide in 2015, a report in The Lancet has found.

Deaths per 100,000 people that are attributable to all forms of pollution, 2015



Pollution is killing more people than wars, obesity, smoking, and malnutrition

Hilary Brueck, Business Insider US
October 24, 2017

Facebook | Twitter | LinkedIn | Email | Print

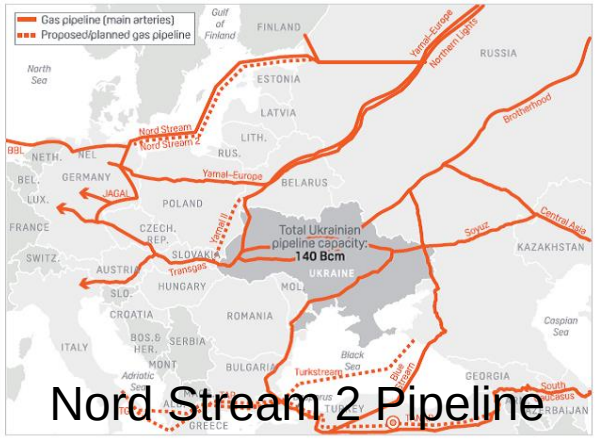
A policeman, wearing a mask to protect from severe pollution. Thomson Reuters

9 million people died prematurely from pollution-related diseases in 2015, accounting for 16% of all deaths worldwide. Almost all of the pollution-related deaths are happening in poor and developing countries. This costs the world an estimated $4.6 trillion a year.

"In addition to the human tragedy, this pollution costs us well over $4 trillion in annual losses, or 6% of global GDP."

Ending the reliance on energy imports will have important benefits.


Suez Crisis



The **Oil** Markets Are At A Confusing Crossroads
OilPrice.com - 7 hours ago
The **oil** market is "adequately supplied for now," but the supply losses from Venezuela and Iran leave the market suffering from "strain," ...

Oil prices rise amid Saudi tensions, but demand outlook drags
CNBC - 1 hour ago

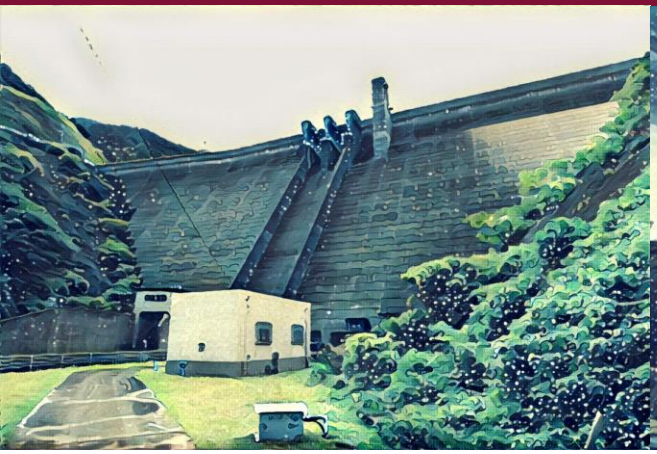
OPEC Thinks the **Oil** Market Is Worried About the Wrong Thing
Motley Fool - 9 hours ago

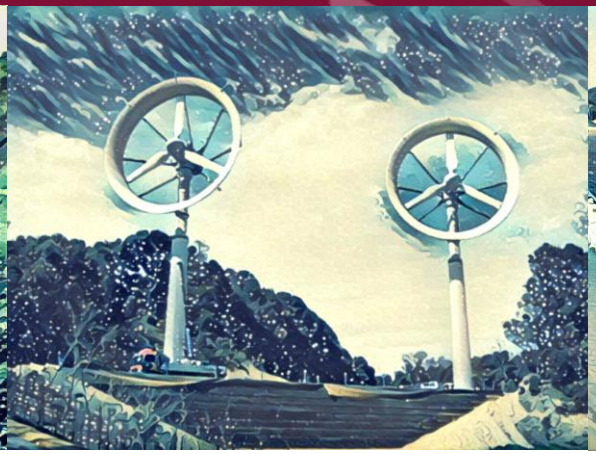
REFILE-UPDATE 1-S.Korea's Sept imports of Iran **oil** fall to zero ahead ...
Reuters Africa - 3 hours ago

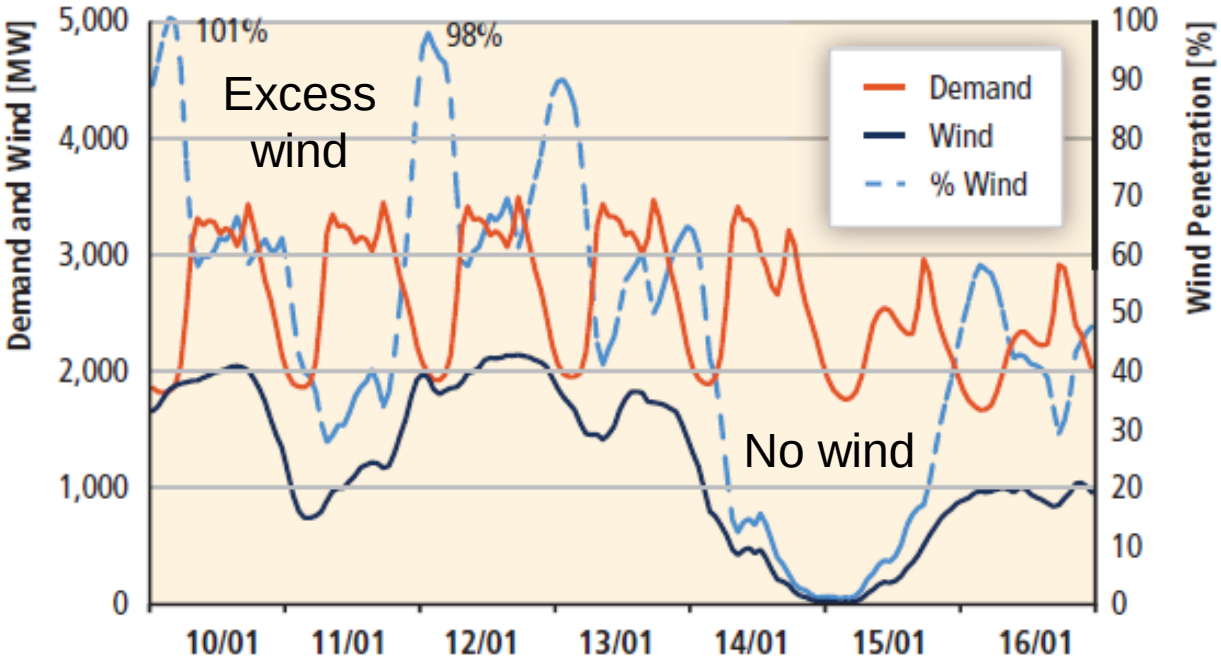
Iran Found New Partners for **Oil** Exports Despite US Sanctions - Vice ...

Oil Shock

Renewable Energy Sources





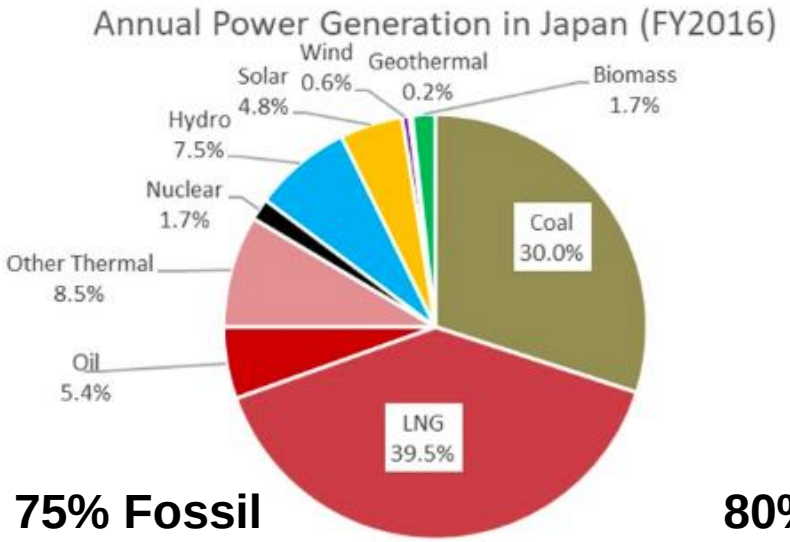


Renewable energy is intermittent.

Mismatch between supply & demand

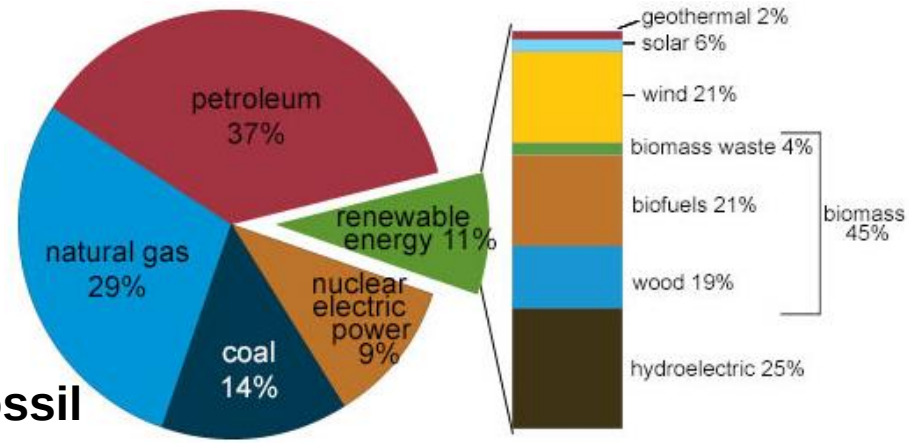
Energy storage for off-peak supply is needed.

What about gas???



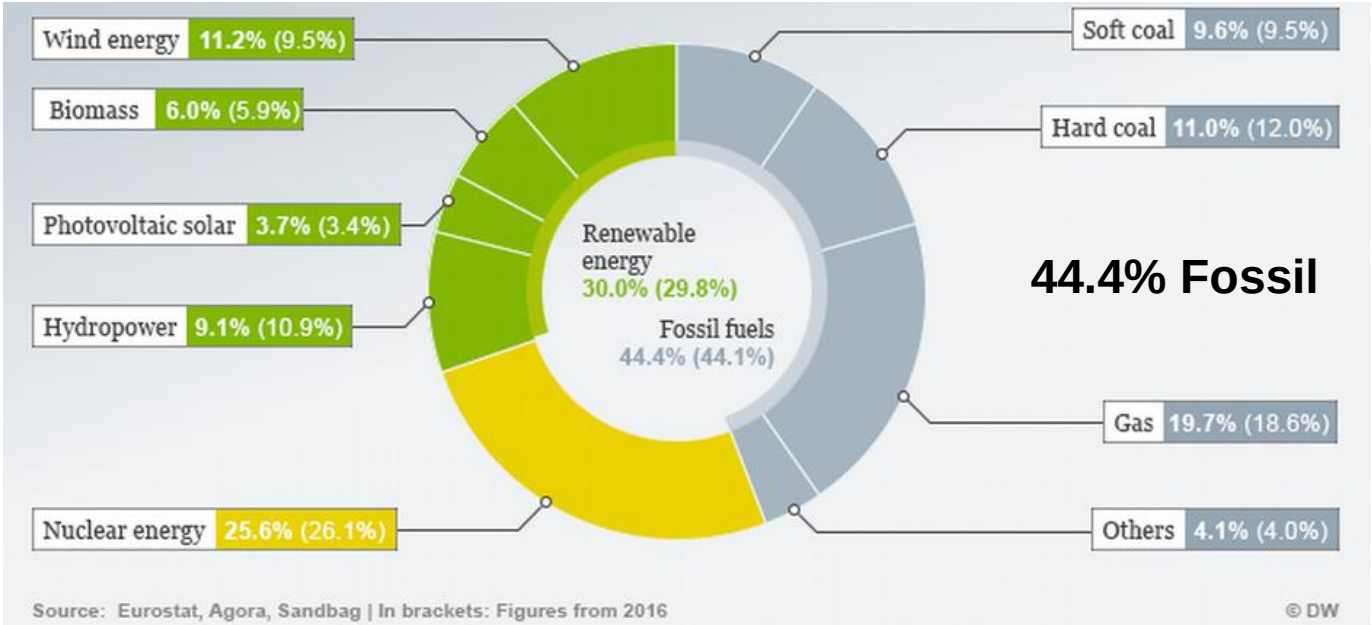
75% Fossil

Annual Power Generation in US (FY2017)

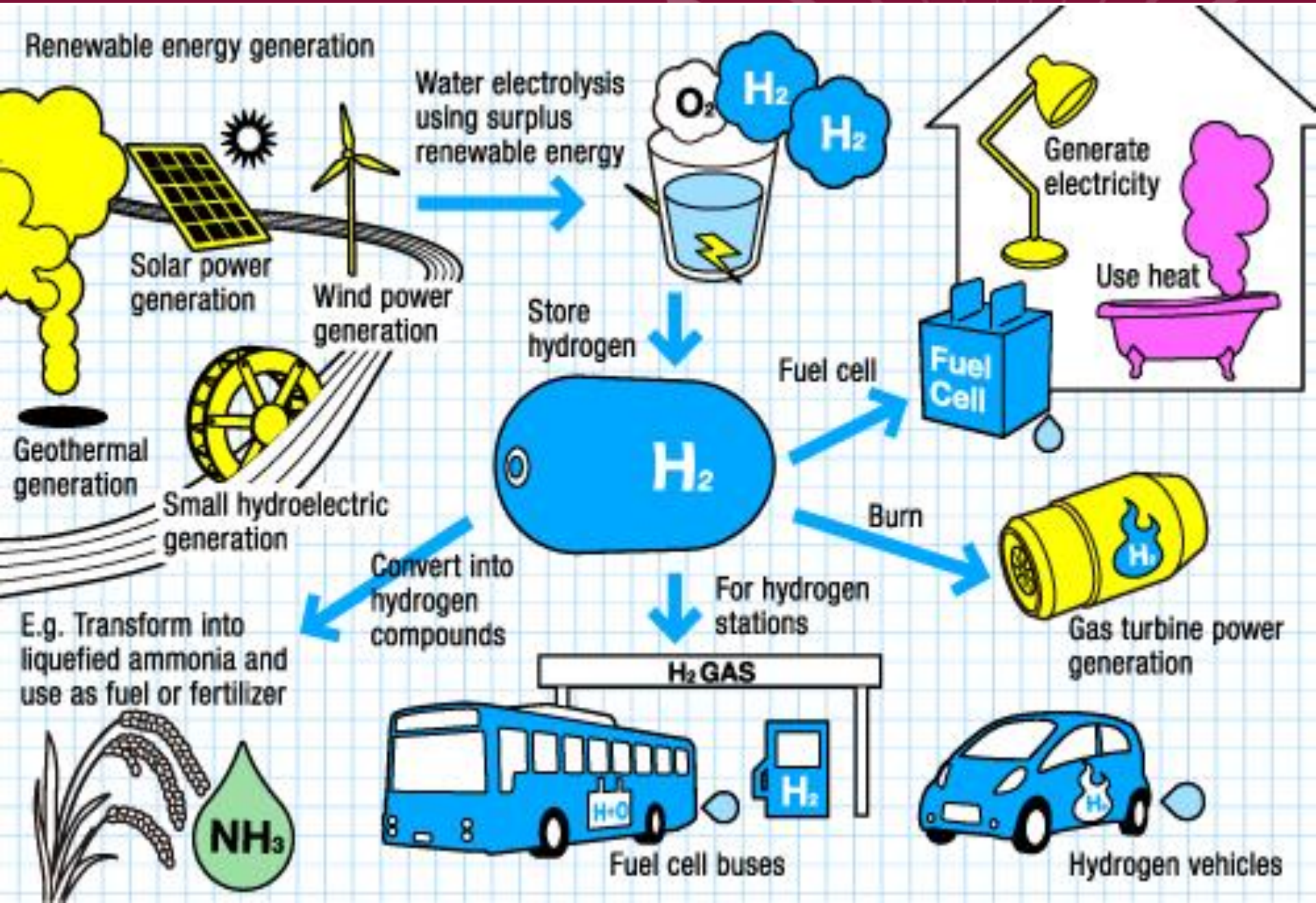


80% Fossil

Annual Power Generation in Europe (FY2016)



The Hydrogen Economy



Fuel Cells

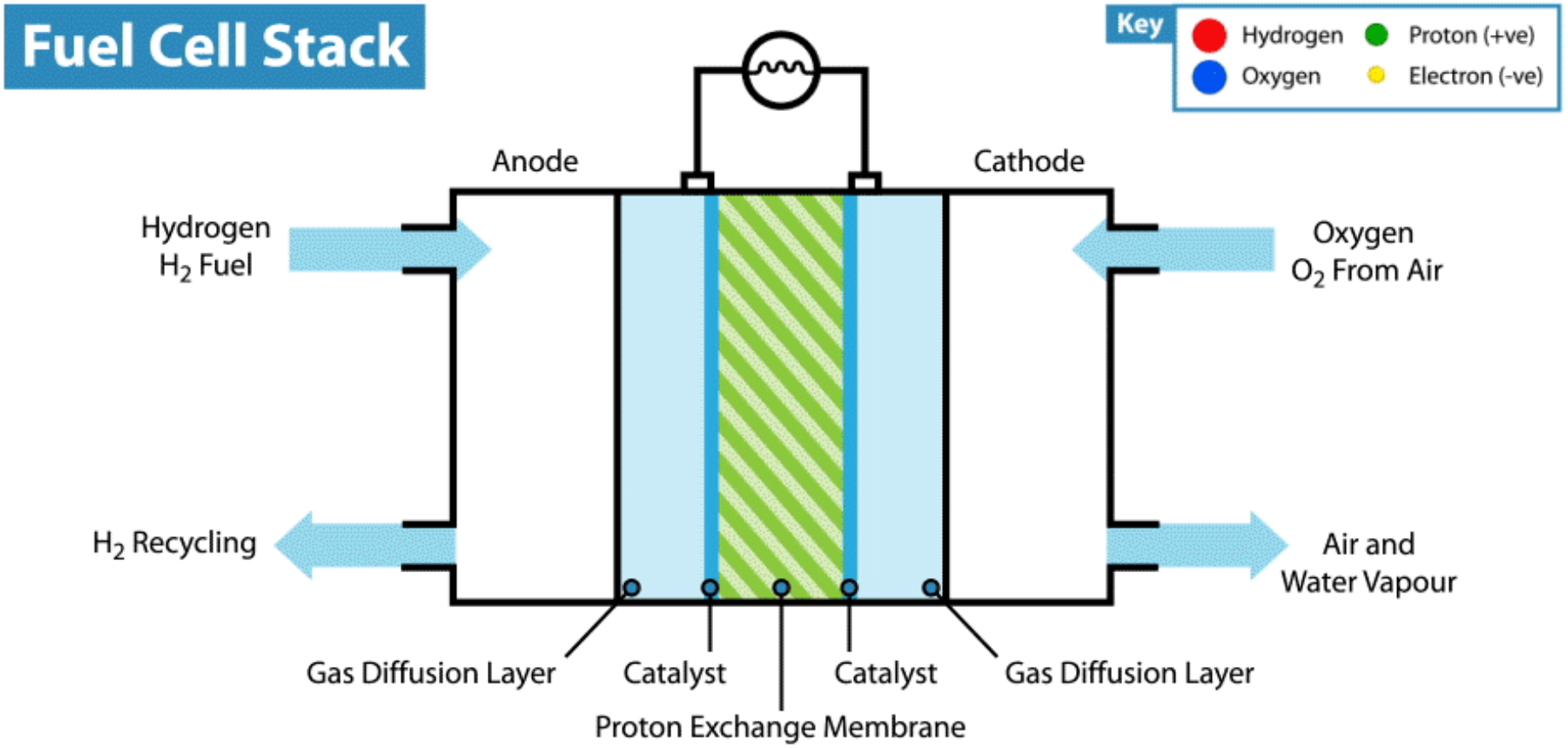
First, who knows how a battery works?

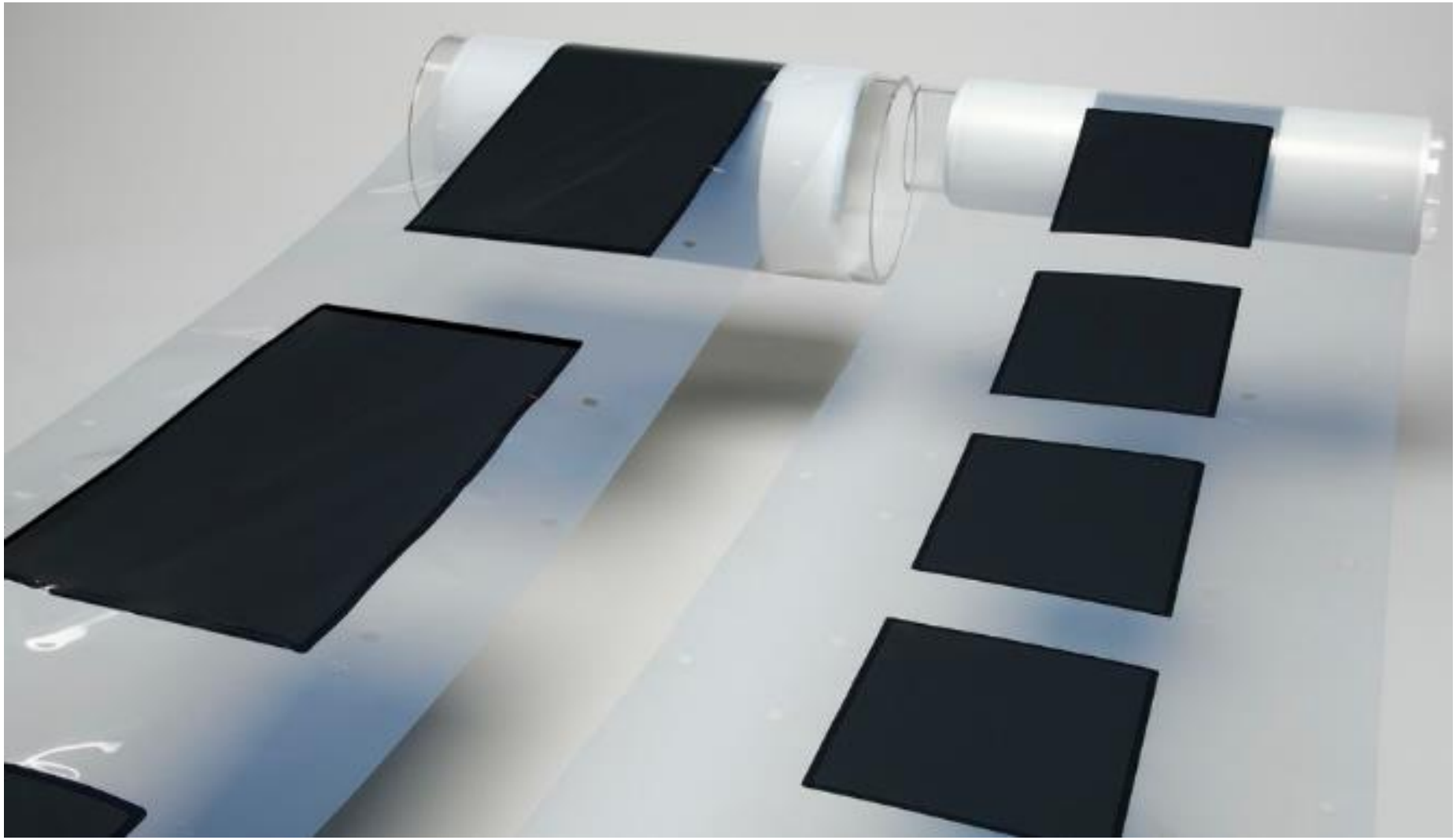
One chemical reaction sucks up electrons

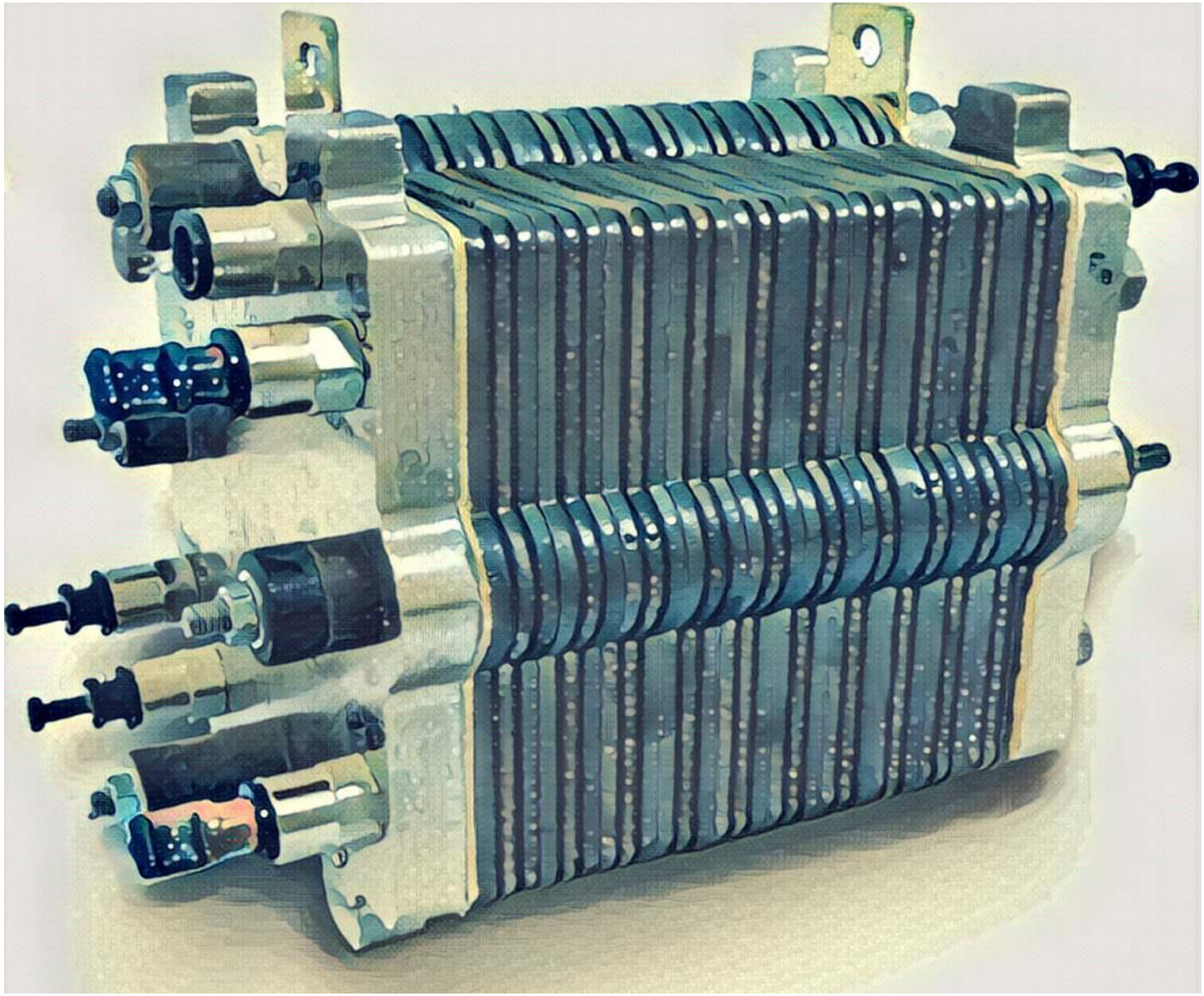
Flow of electrons between the electrodes is electric current.

The other liberates electrons

Polymer Electrolyte Membrane Fuel Cells

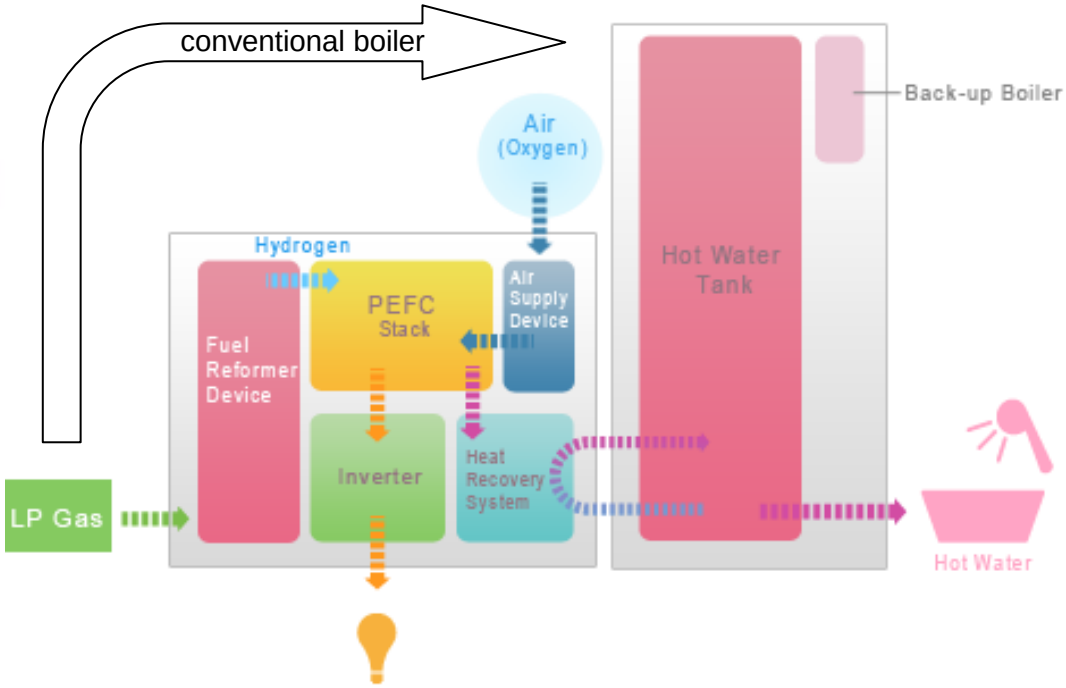






ENE-FARM: Residential Fuel Cells

ENE·FARM エネファーム type S

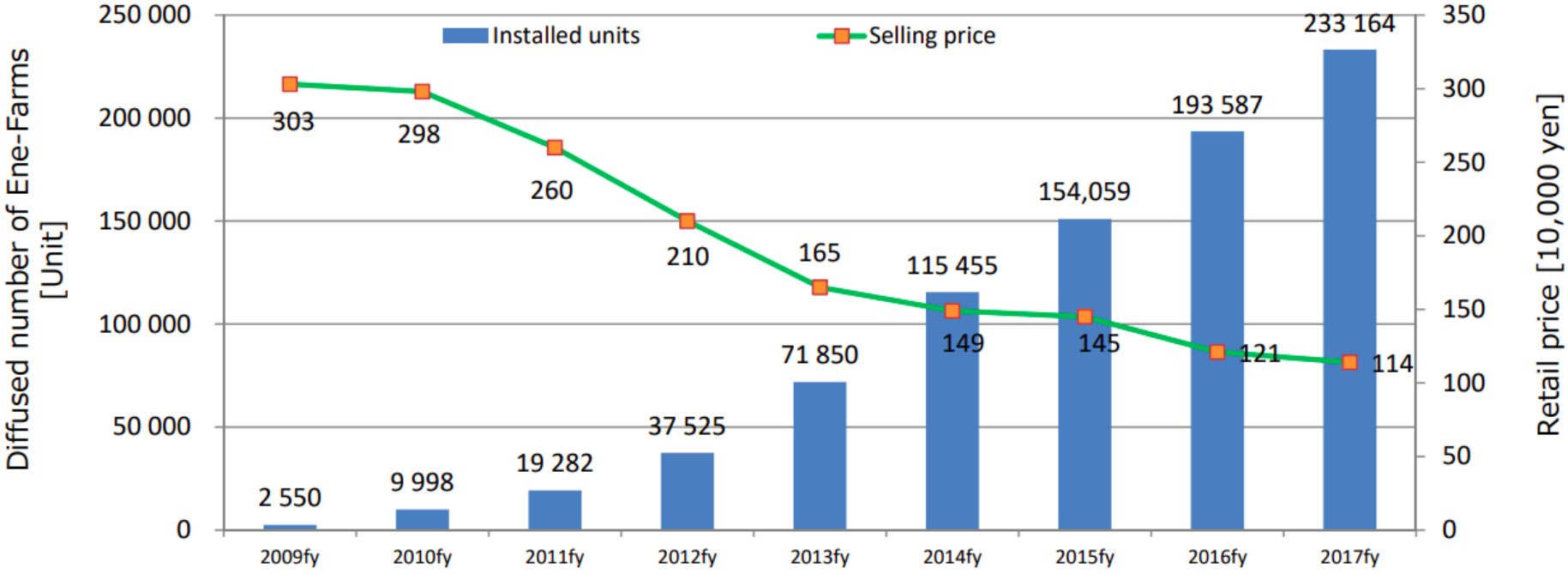


>220,000 units sold
~0.5 % of households
Aisin, Panasonic (+Toshiba)

1,100,000 JPY

METI ENEFARM Unit Cost Targets:

- **2018**: 11,000 USD (11 years investment return)
- **2020**: 8,000 USD (8 years investment return)
- **2030**: 5,000 USD (5 years investment return)



* Based on determination subsidization base

(As of the end of January 2018)

Reduction in system price has stalled.
Disruptive technologies are required to meet cost targets.

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Toyota MIRAI = 未来 = FUTURE

15 December 2014

502 km (312 mi), 79 mpg$_{\text{-imp}}$
114 kW (153 hp), 370 cells

6,700,000 JPY!

Katsuhiko Hirose
Project General Manager, Fuel Cell System Development Division
And **WPI Visiting Professor at Kyushu Univeristy**

Available for sale in the UK, Denmark, Germany, Belgium, and Norway

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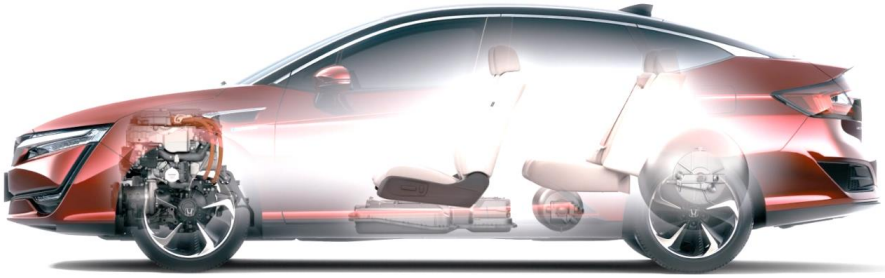
Honda Clarity FC

10 March 2016

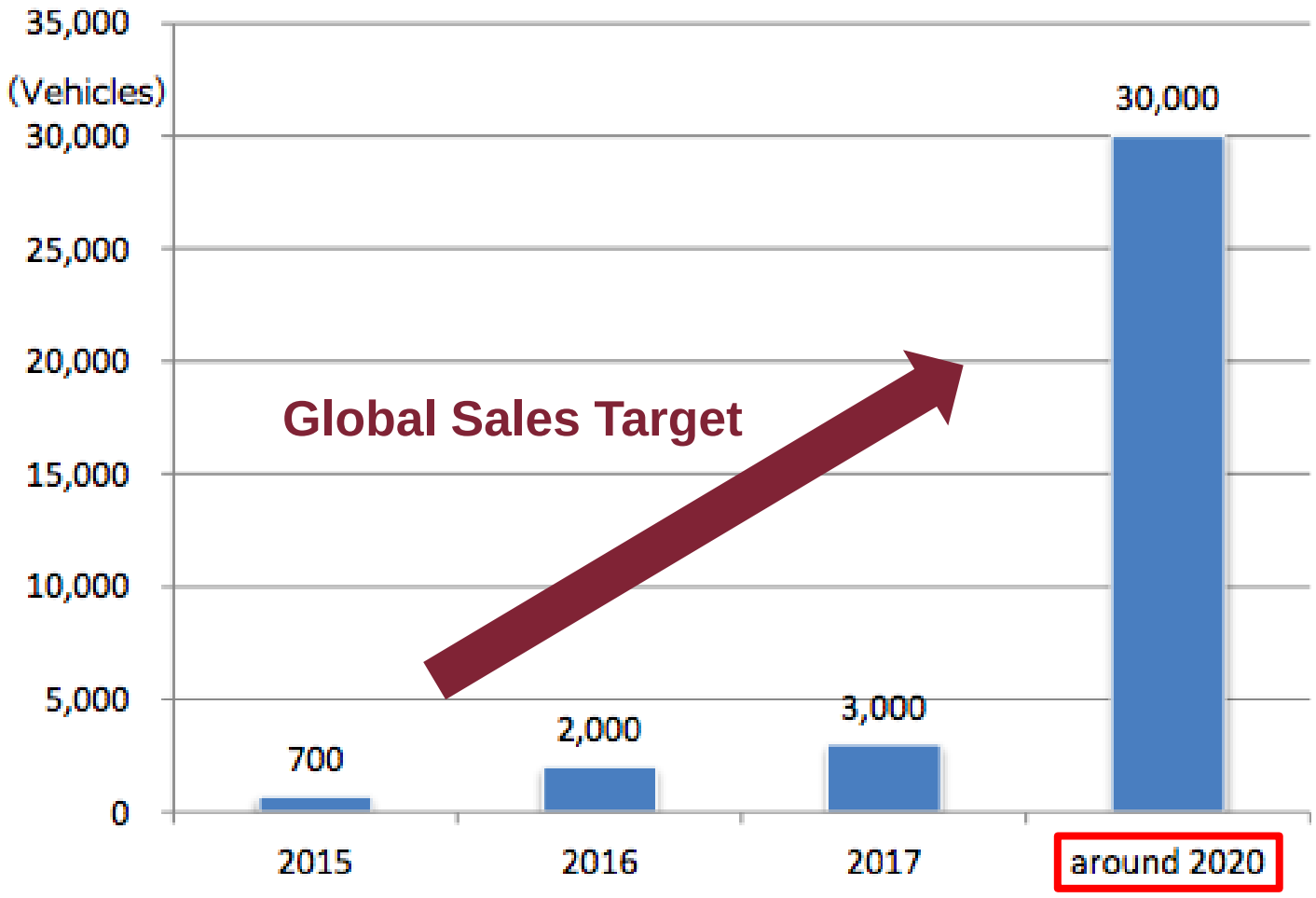
590 km (366 mi)
130 kW (174 hp)



7,600,000 JPY!

Fuel Cells Vehicles

Toyota's expected global sales of FCVs (Single year)



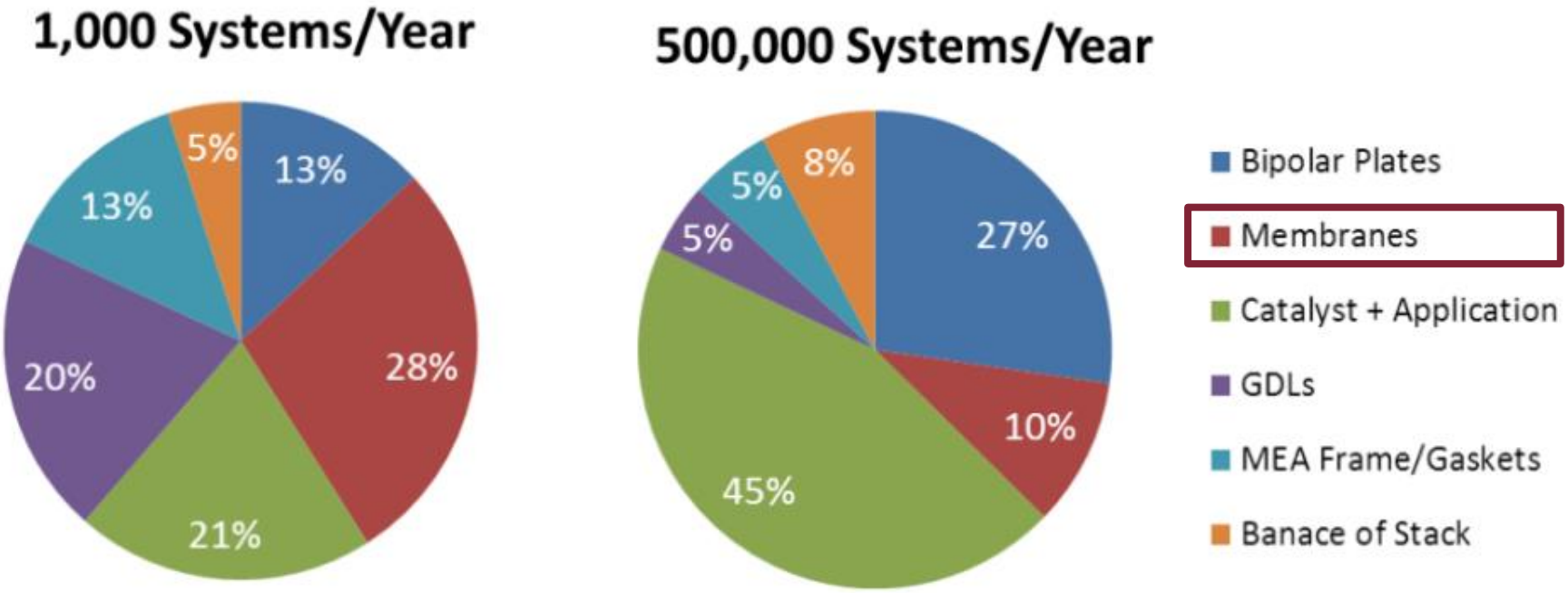
Source: METI, Japan

Can hydrogen and fuel cells really impact society?

- Easy to take privileged position in Japan for granted.
- Fuel cell technologies are still extremely expensive.
- They should be for the many, not a select few.
- Otherwise, they will have little positive impact.

$11,000 $67,000 $76,000

Why are fuel cells expensive?



10 to 28% is due to the *Nafion* electrolyte
Nafion in MIRAI: 525,000 JPY
Nafion in ENEFARM: 52,000 JPY

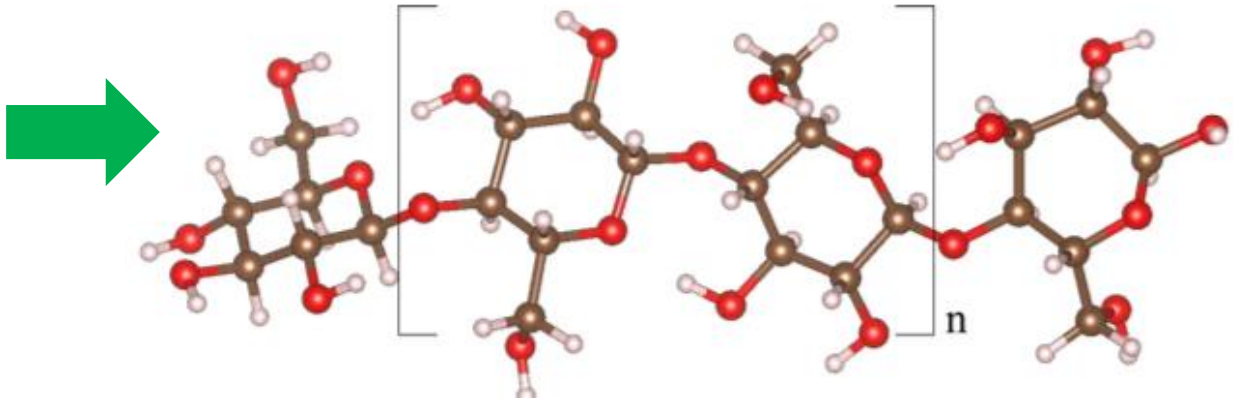
The ultimate goal is that the hydrogen economy can reach all parts of the world.

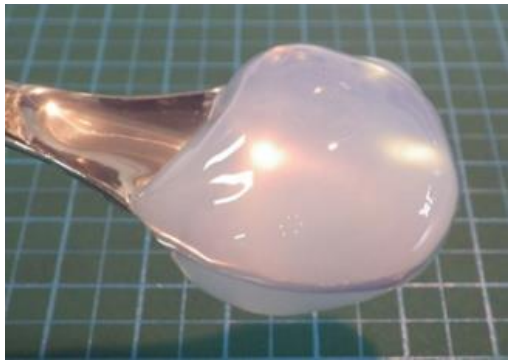
e.g.

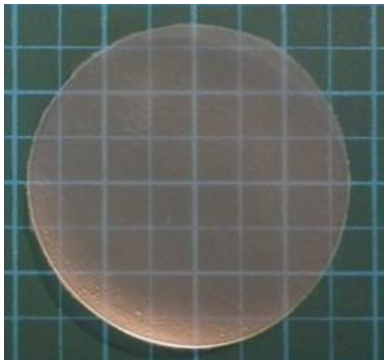
FUEL CELL AUTO RICKSHAW

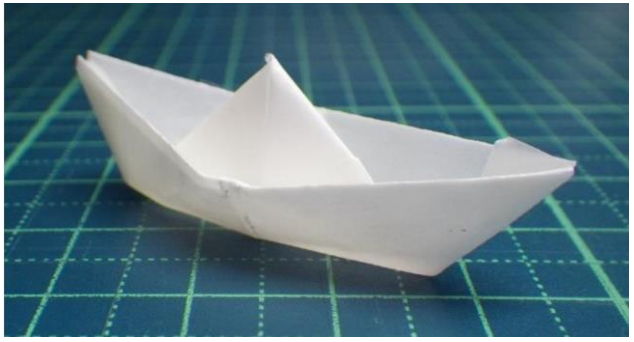
Nanocellulose: Paper Membranes

Nanocellulose Membranes









Abundant biopolymer
Extremely cheap
Green (oil free)

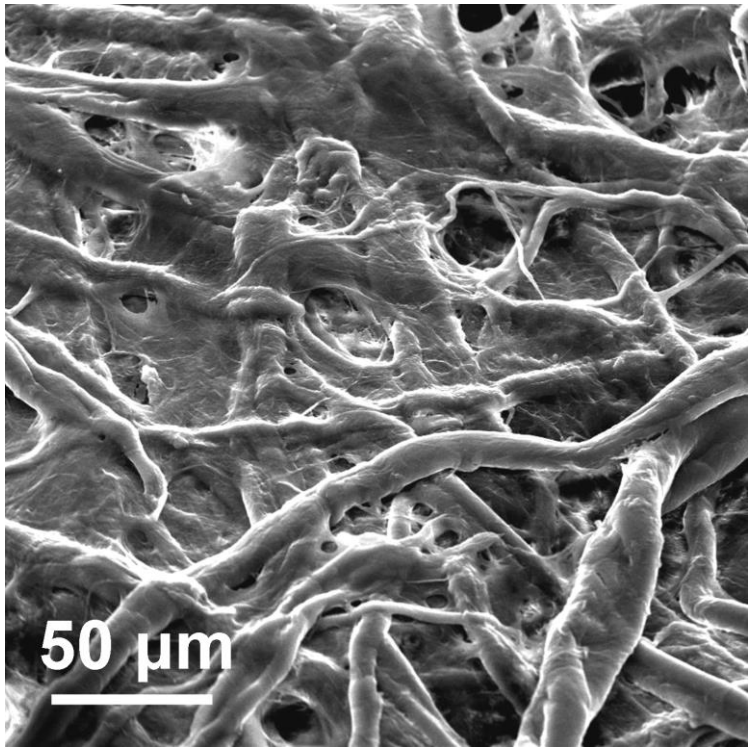
Strength: 4 x Nafion

Hydrogen permeability:
1000x lower than Nafion

T. Bayer et al. / Chemistry of Materials (2016)

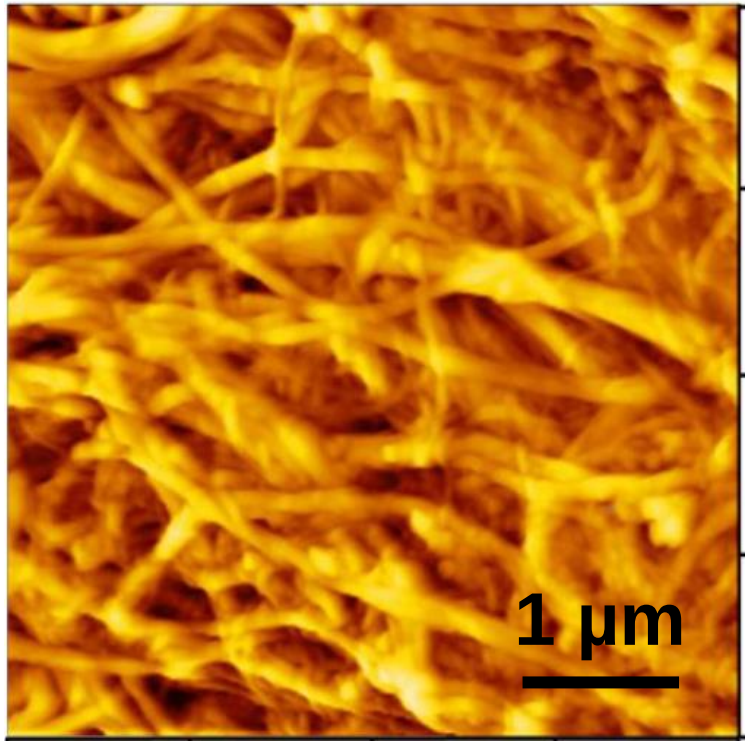
Morphology of Nanocellulose Fibers

Conventional Paper



10 µm fibers

Nanocellulose Paper



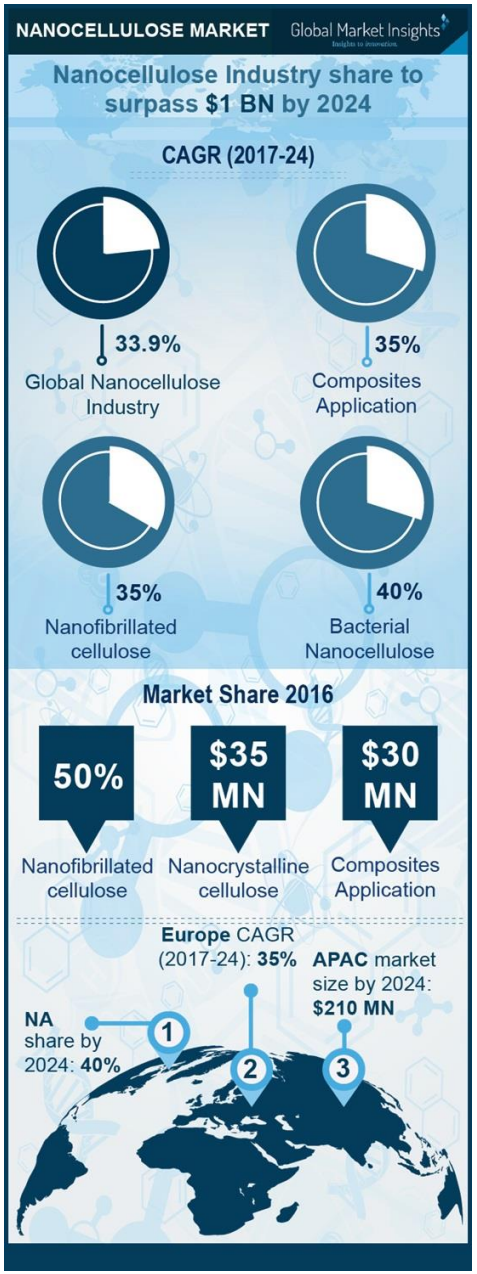
100 nm fibers

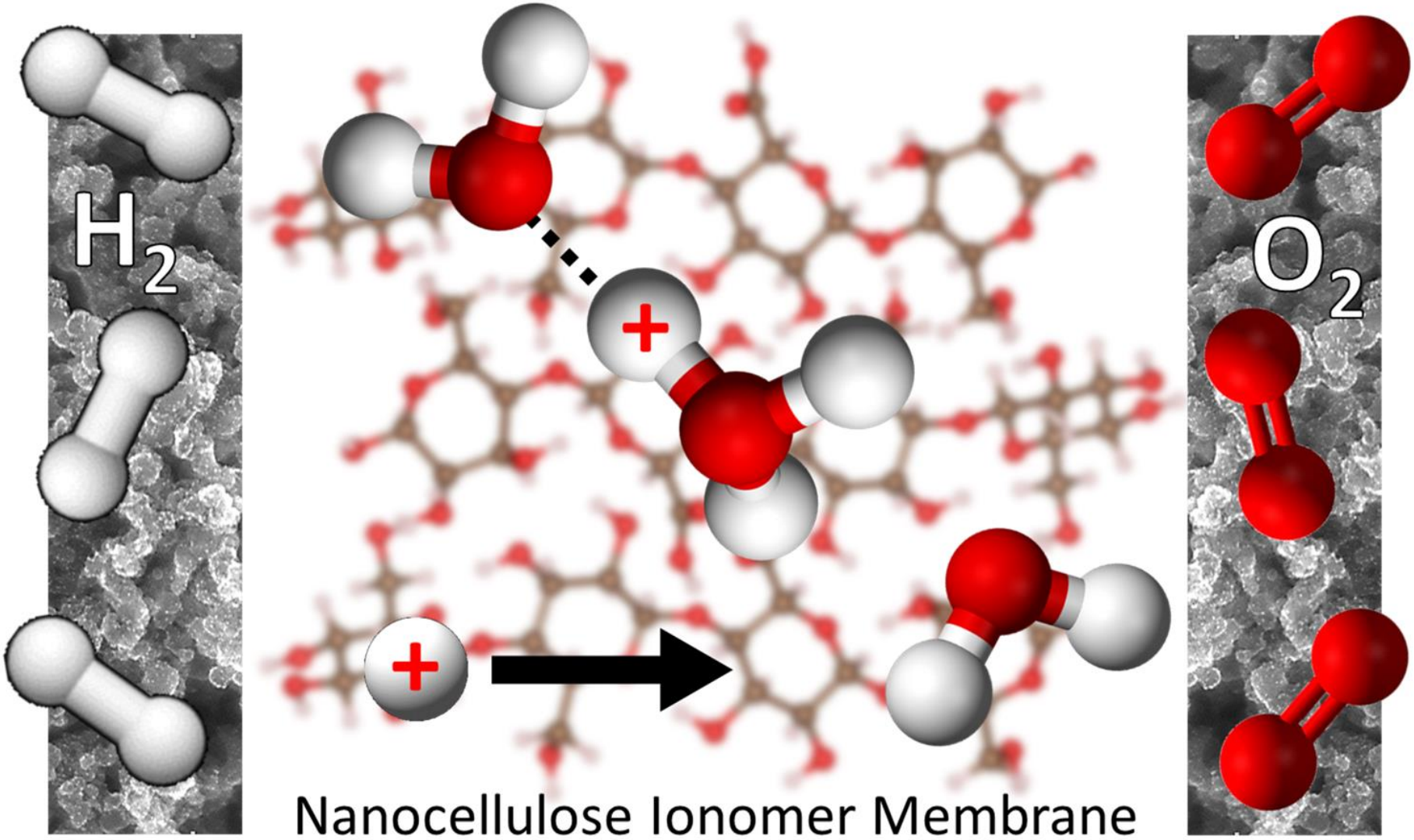
T. Bayer et al. / Chemistry of Materials (2016)

343938 Keyword: ”cellulose”

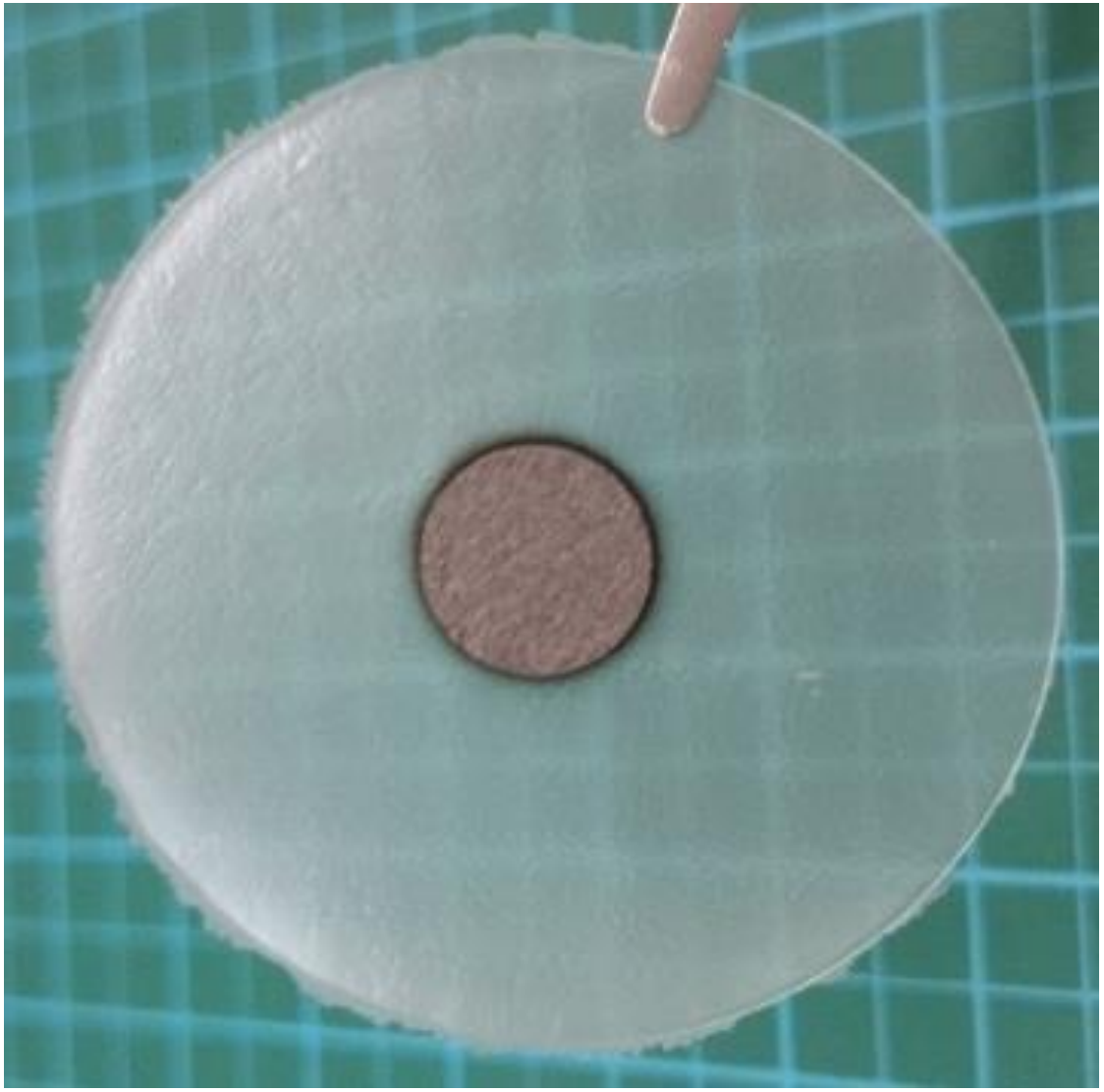
patent documents worldwide

Billion dollar market by 2024.

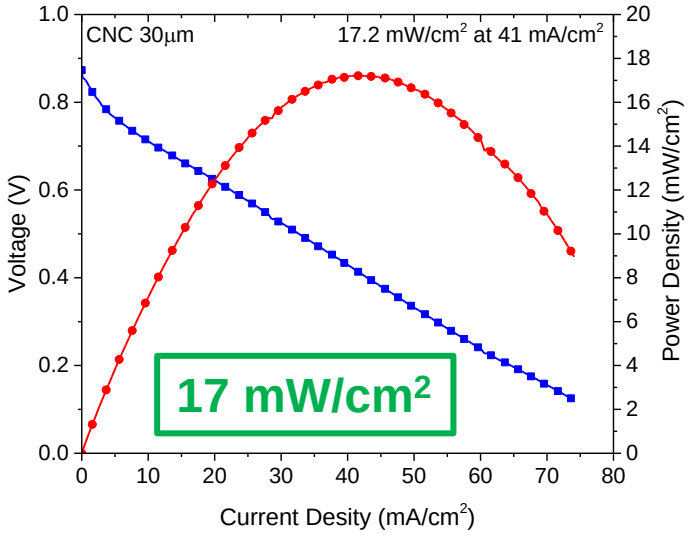


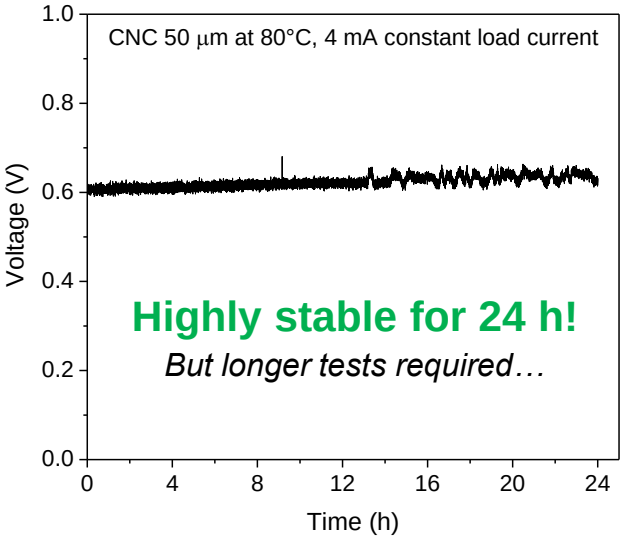

H_2
O_2
Nanocellulose Ionomer Membrane

Nanocellulose Fuel Cells



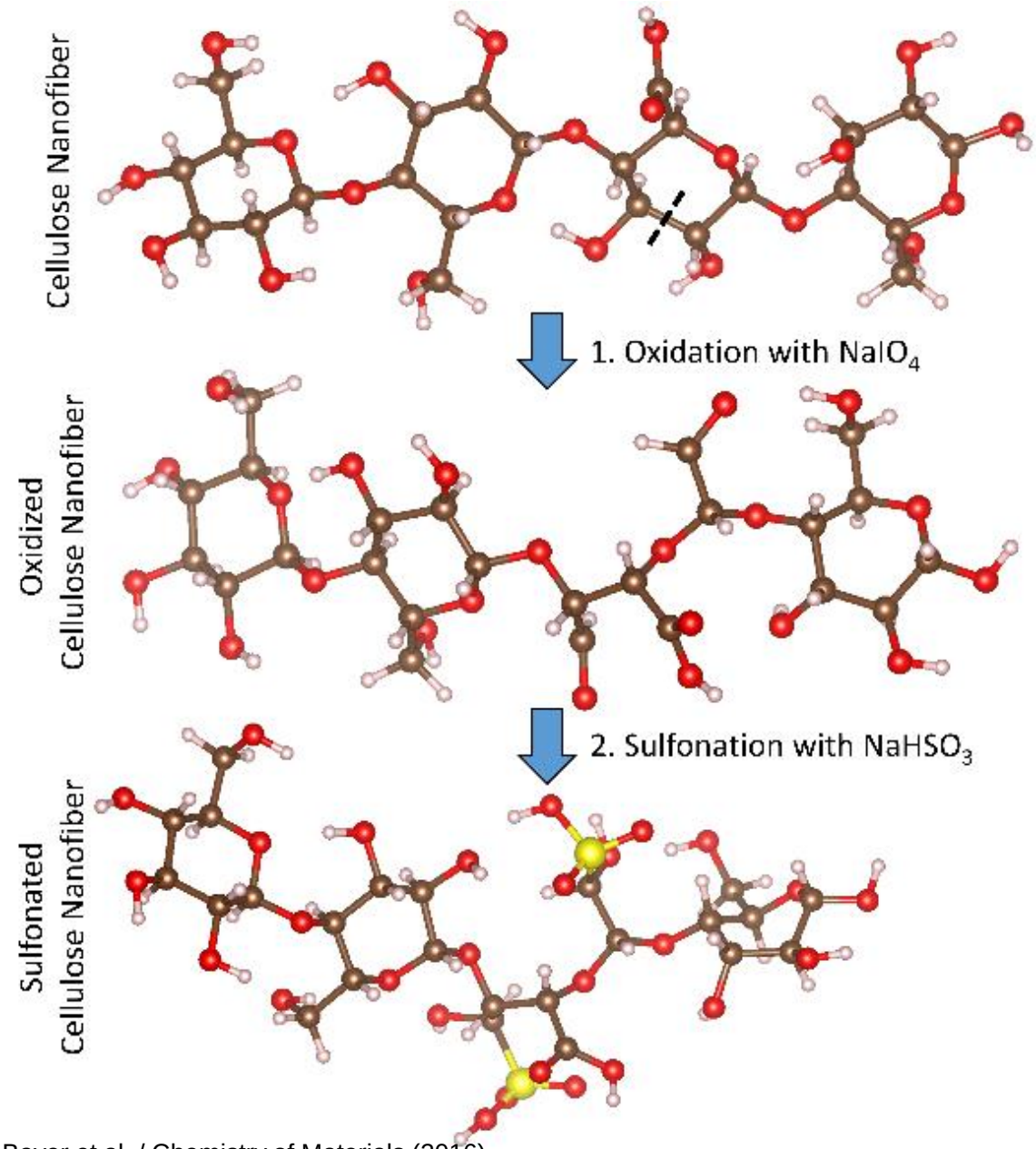
2016: World's first paper fuel cell!

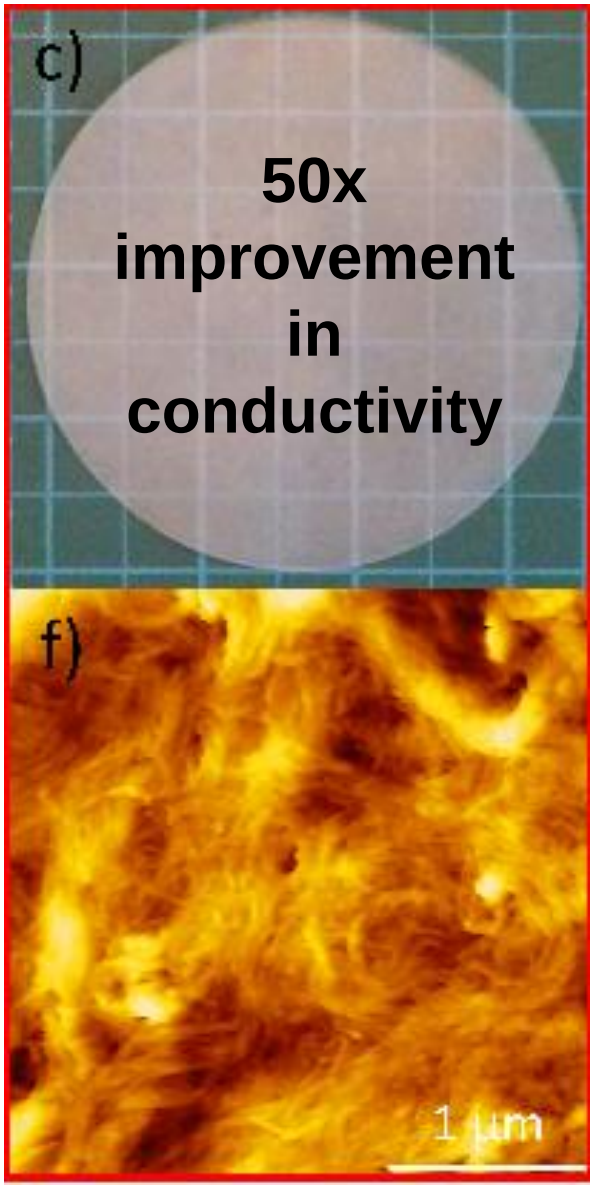




T. Bayer et al. / Chemistry of Materials (2016)

Innovation 1: Sulfonation



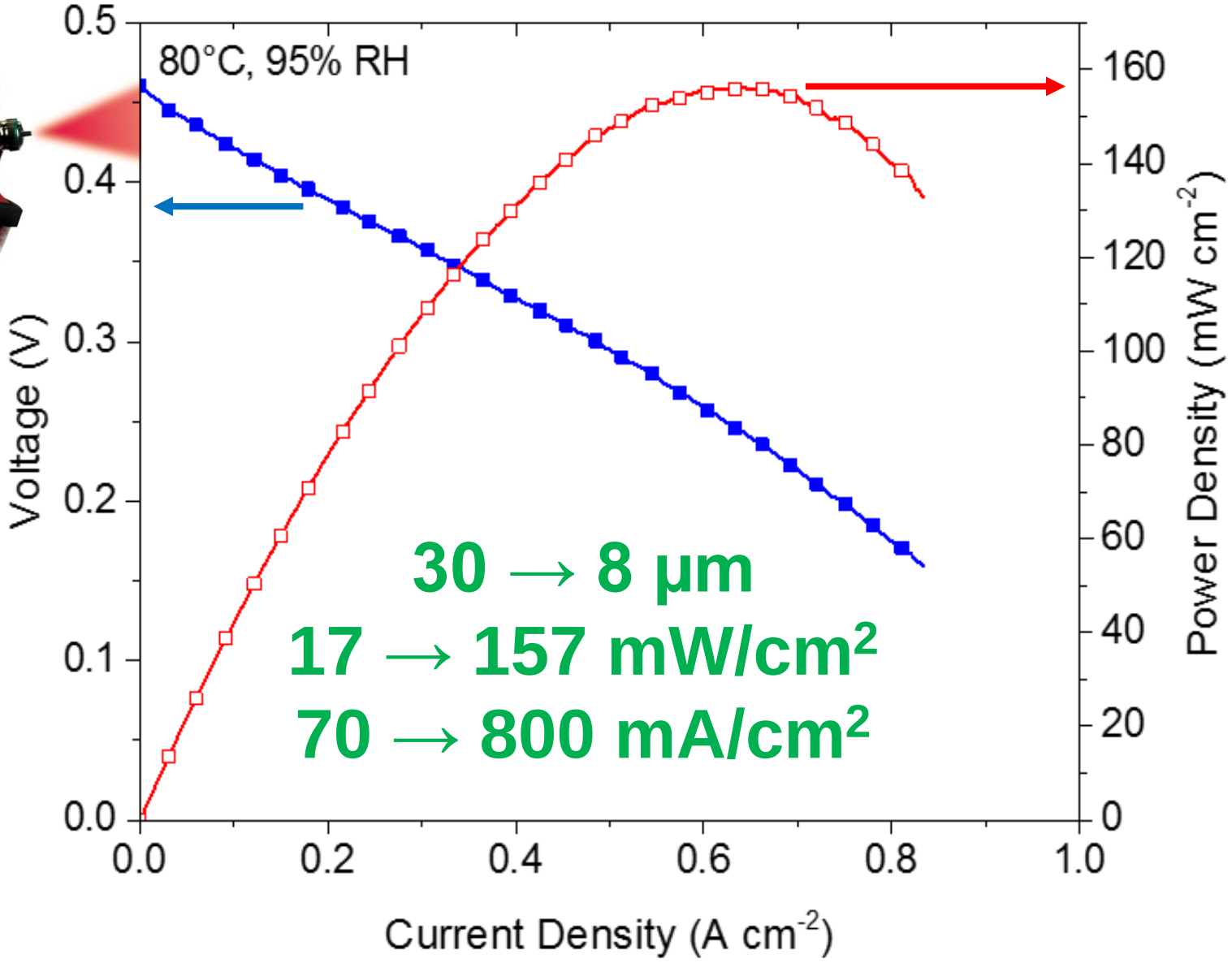


T. Bayer et al. / Chemistry of Materials (2016)

Innovation 2: Spray Printing

4x decrease in thickness (reduced resistance)

Sulfonation + Spray Printing



Some way to go to compete with Nafion.

But huge potential cost savings.

Cost / performance trade-off.

Kyushu University GAP Fund

KU GAP Fund (2018 - 2nd Year)

University-Initiated Venture Business Seed Development Program

- Creation of university-initiated ventures based on research results of entrepreneurial faculty members.
- Integrate **customer evaluation** which is where university initiated ventures are most likely to fail.
- 10 projects/year, 2 million yen, 7 months duration.
- Faculty aged 30-40 represent 80% of all applications.
- Company formed after positive customer evaluation.

Primary Evaluation (Document Screening)

No.	事業シーズの名称				申請者所属		
7	Inexpensive Fuel Cells: Replacing Sulfonated Fluoropolymers with Cellulose				エネルギー研究教育機構		
順位					申請者氏名		
9位/14件中					Lyth Stephen （准教授）		
	1 事業性	2 実現性	3 戦略性	4 優位性	5 市場性	6 将来性	合 計
審査員A	5	3	3	4	4	4	23
審査員B	5	4	4	4	4	5	26
審査員C	3	3	3	5	4	5	23
審査員D	4	4	3	4	4	3	22
審査員E	4	5	3	3	5	4	24
審査員F	5	4	4	4	3	3	23
審査員G	6	5	5	5	5	5	31
審査員H	6	5	4	6	6	6	33
平 均	4.75	4.13	3.63	4.38	4.38	4.38	25.63

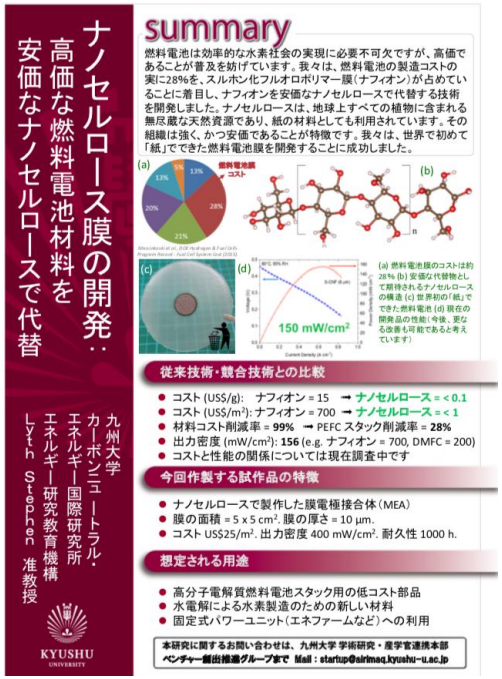
※赤表示は最高点、青表示は最低点

Secondary Evaluation (Interview Feedback)

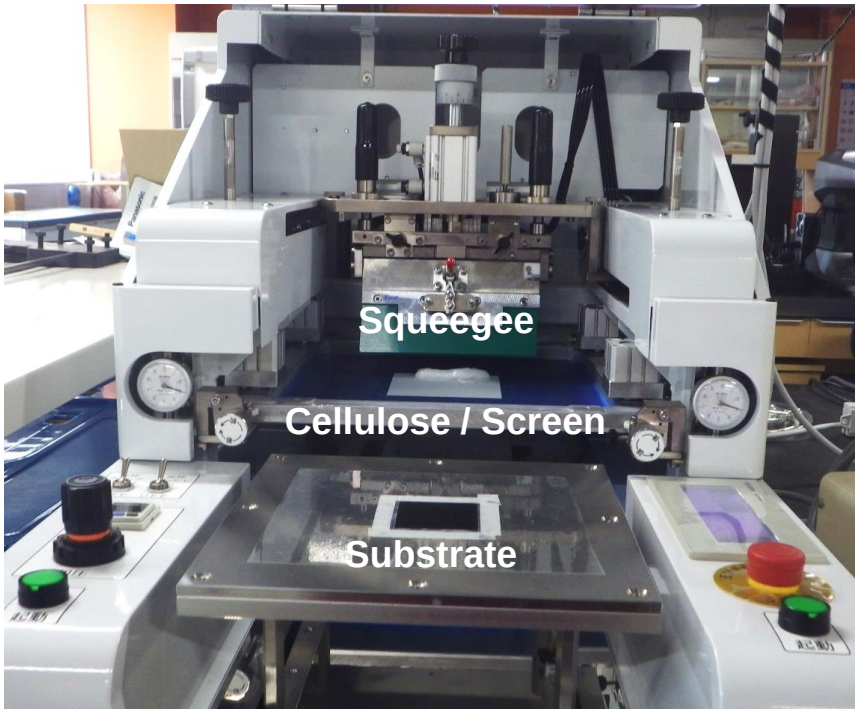
総合評価	事業シーズの名称					申請者所属			
OVERALL RANKING 9 位	Inexpensive Fuel Cells: Replacing Sulfonated Fluoropolymers with Cellulose					エネルギー研究教育機構 Q-PIT			
（参考）一次審査						申請者氏名			
1st ROUND RANKING 9位 RANKING						Lyth Stephen （准教授）			
	JUDGE 審査員A	審査員B	審査員C	審査員D	審査員E	審査員F	審査員G	TOTAL 合 計	RANK 順 位
FEASIBILITY 事業性	5	5	4	4	4	5	5	32	8 位
POSSIBILITY 実現性	4	4	5	4	5	5	4	31	7 位
STRATEGIC 戦略性	4	5	4	3	3	5	4	28	10 位
SUPERIORITY 優位性	4	4	5	4	4	4	5	30	7 位
MARKETABILITY 市場性	4	4	4	4	5	5	5	31	5 位
FUTURE 将来性	4	4	4	4	4	5	5	30	9 位
TOTAL 合 計	25	26	26	23	25	29	28	182	9 位

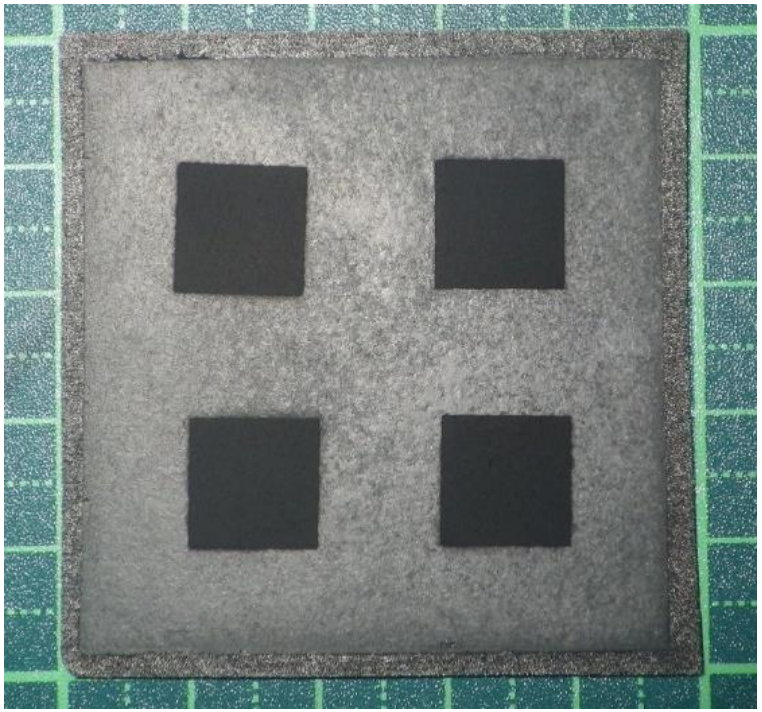
Academic Research and Industrial Collaboration Management Office

- Manage press releases
- Matchmaking with VC (banks) and tech companies (utilities).
- Support during meetings.
- Legal advice.



Current Status: Screen Printing

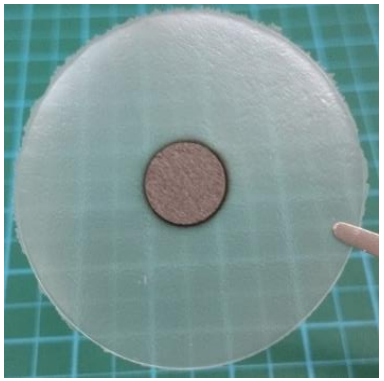




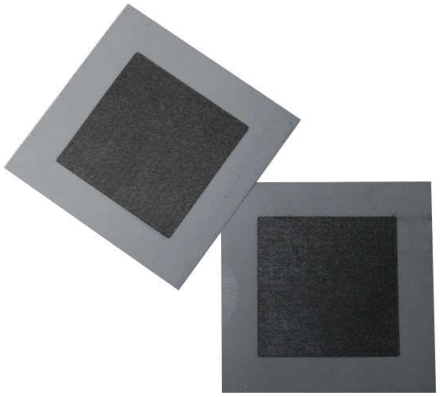
- **Switched from spray deposition to screen printing**
- **Large area, uniform films, reproducible, cheap.**
- **Industrialized thinking catalyzed by start-up fund.**

Future Targets

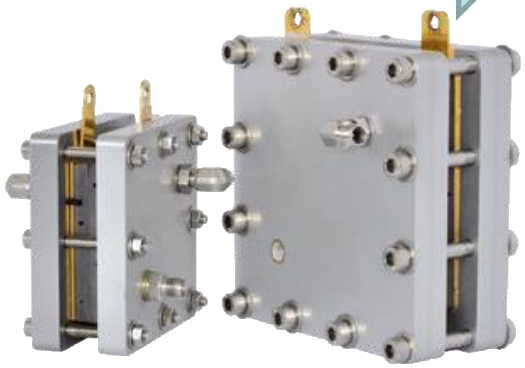
Product Development



2017 status



Current Status:
MEA (4 x 4 cm)



Mid-term target:
MEA Stack 250 W

Long-term target:
System integration

Prototype Targets (November 2018)		Current Status
Power Density:	400 mW/cm^2	157 mW/cm^2
Active Area:	4 cm^2	4 cm^2
Hydrogen Crossover:	< 2 mA/cm^2	0.5 mA/cm^2
Open Circuit Voltage:	0.7 V	0.97 V
Durability:	1000 hours	24 hours

Issues

- First patent application in Japanese a huge amount of time, confusion, effort and cost.
- Short Time Scale: 7 months for prototype development, finding customers, arranging customer evaluation.
- Customer evaluation required before company formation.
- First foreign applicant. Don’t have business Japanese to interact with companies (VC / banks / tech).
- Conservatism of Japanese companies. Wary of academics / young faculty / foreigners.
- Lack of clarity about conflicts of interest between academic / business (how faculty can make money).

Summary

- Renewable technologies and hydrogen will mitigate climate change and improve air quality.
- Fuel cells should be widely available, but they are far too expensive.
- Nanocellulose can replace expensive fuel cell membranes.
- We made world first “paper fuel cells”.
- Potential savings of 28% of fuel cell stack cost.
- Start-up is work-in-progress.

“Money doesn’t grow on trees”

“Nanocellulose does”

金は木に生えない。木はナノセルロースからできています。

[Kin wa ki ni haenai. Shikashi, ki wa nanoserurōsu kara dekite imasu.]

Thank you for your time!