Membrane Science and Technology for Hydrogen Applications

by Prof D Bessarabov
HySA CoC Director

Inaugural scientific address

15 October 2021

HySA Infrastructure
Hydrogen South Africa

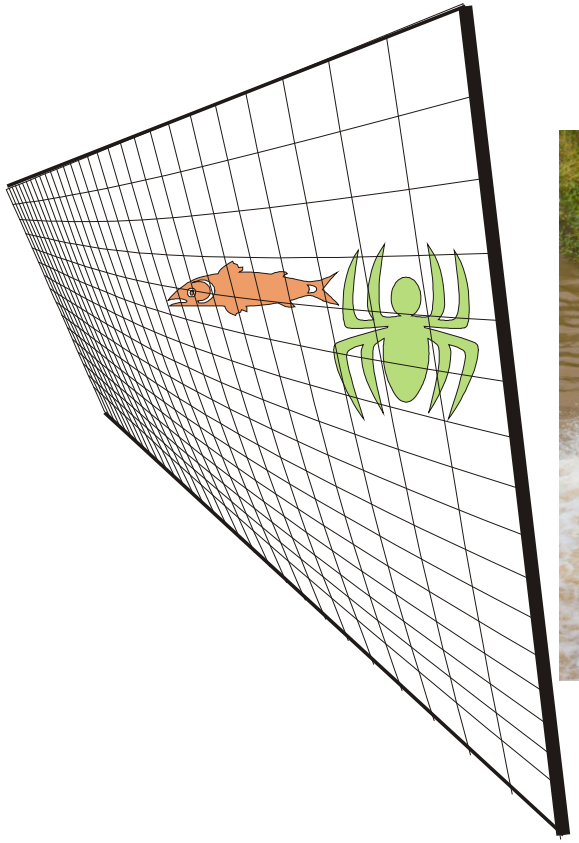
“In the 1920s, there was a dinner at which the physicist Robert Wood was asked to respond to a toast ... **'To physics and metaphysics!**’
By metaphysics was meant something like philosophy—truths that you could get to just by thinking about them. Wood took a second and answered along these lines: *The physicist has an idea*, he said. *The more he thinks it through, the more sense it makes to him. Thus prepared, he devises an experiment to test the idea. The experiment is painstaking, many possibilities are eliminated; the accuracy of the measurement is refined. At the end of all this work, the experiment is completed and ... the idea is shown to be worthless. The physicist then discards the idea, frees his mind from the clutter of error, and moves on to something else.* **The difference between physics and metaphysics, Wood concluded, is that the metaphysicist has no laboratory**.”

This lecture is not only about hydrogen or membranes, but a journey where laboratory “toys” get bigger and bigger, and these “toys” are part of my life and memories....

TOC

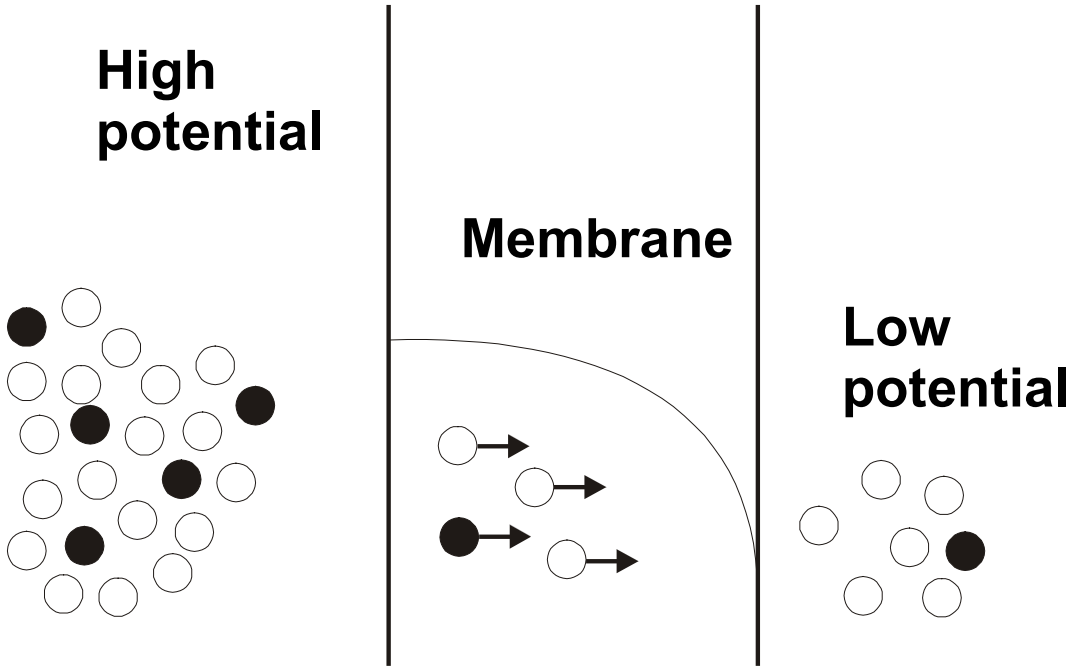
- Preface and background
- Membranes, Hydrogen and Personal Vision
- Membranes and Wonders in Nature and in Engineering
- Membranes for Hydrogen
- Importance of Hydrogen

Definition of a membrane. What is a membrane?



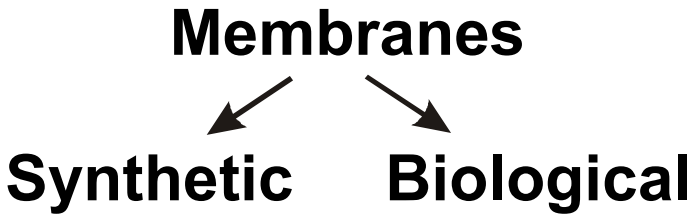
Membrane. Definition.

- **A SELECTIVE barrier separating two phases**
- It is a "macroscopic" definition, does not say anything about structure and/or function of a membrane



How do we classify membranes ?

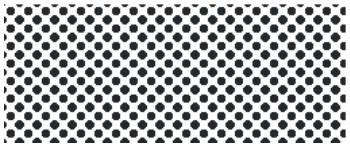
- By type? (e.g., asymmetric, hollow fiber, porous, dense, etc)
- By separation process? (e.g., liquid separation, vapour, gas, etc)
- By nature ? (e.g., organic, inorganic, etc)
- By transport phenomena (e.g., active, passive)
- By charge (e.g., neutral or charged)
- By driving force (e.g, pressure gradient, concentration gradient)



Morphology of synthetic membranes

Symmetric

Homogeneous



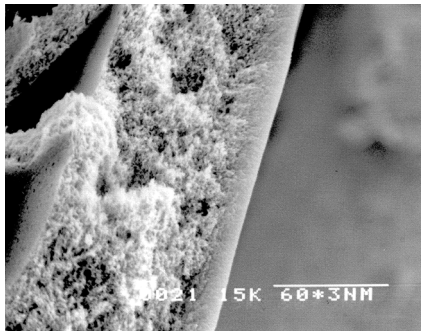
Porous

Cylindrical porous

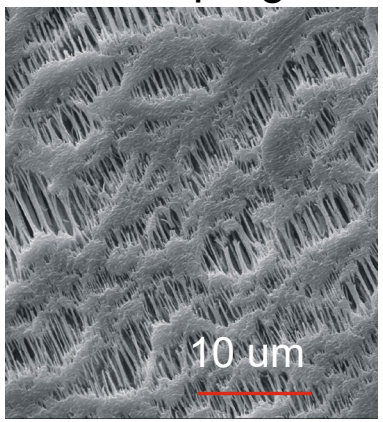
Asymmetric

Selective skin layer

Support layer

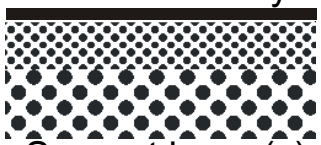


Porous impregnated



Asymmetric composite (TFC)

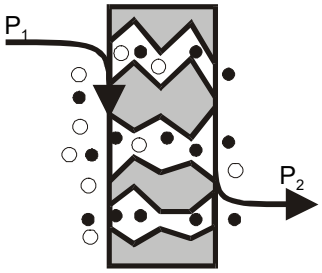
Selective skin layer



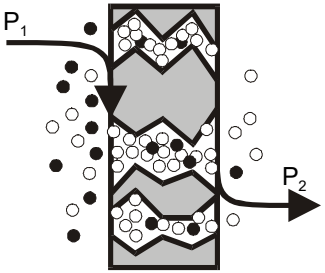
Support layer (s)

Types of mass transport in “non-reactive” membranes

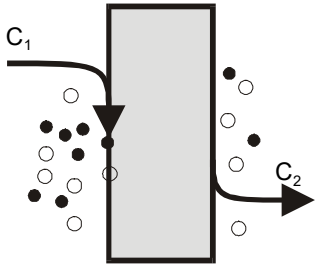
KNUDSEN FLOW



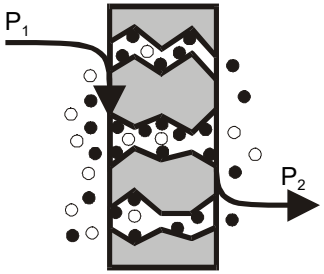
CAPILLARY CONDENSATION WITH GAS FLOW



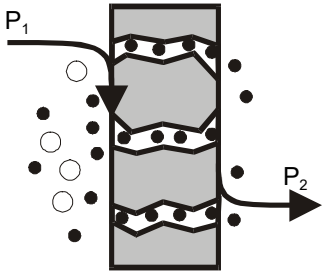
SOLUTION-DIFFUSION



SURFACE FLOW

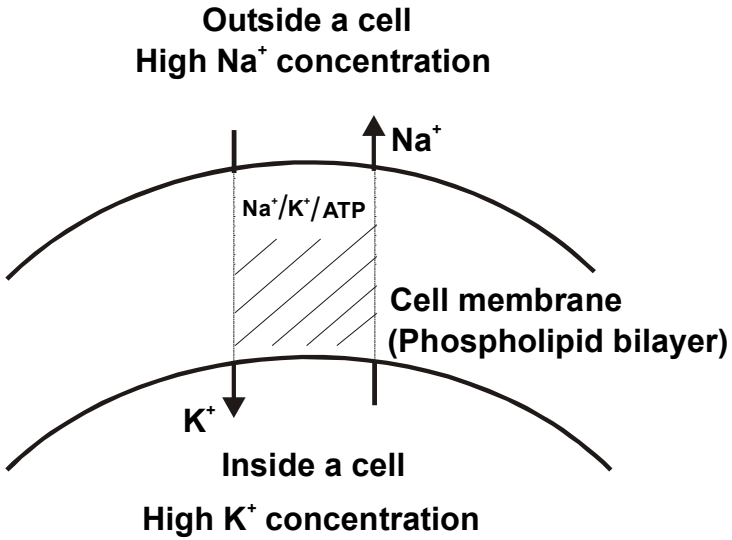


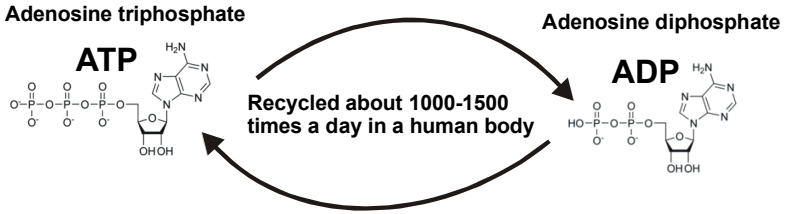
MOLECULAR SIEVING



Miracles of Nature (from the Engineering point of view).

- Biological membranes are a rich mixture of lipids, proteins, and other molecules.
- The self-assembling lipid bilayer accounts for the thinness of the membrane (typically ~ 5 nm).
- Ability to sustain a trans-membrane electrical field of > 10 MV/m (mega V = 1 million volts !), (Compare with 1.2V and 25 μm Nafion, 48kV/m)
- Movement of ions through channels: takes some 10^{-7} s to pass through from one side to the other.





"Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are a part of the mystery that we are trying to solve" **Max Planck**

How Membranes work in Nature? Worth of the Nobel Prize.

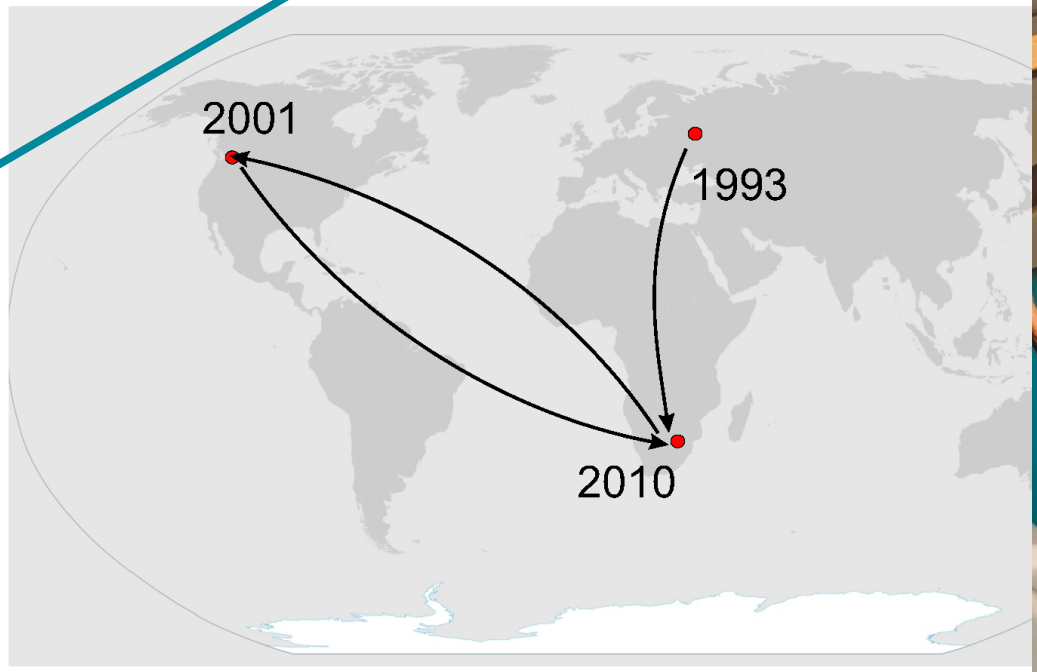
- Two American scientists shared the 2003 Nobel Prize in **Chemistry** for making key discoveries concerning how water and ions are transported through cell membranes.
- **Peter Agre** (Johns Hopkins School of Medicine) was honored for isolating a cell membrane protein that serves as a channel for transporting water.
- **Roderick MacKinnon** (Howard Hughes Medical Institute at The Rockefeller University) was recognized for determining the spatial structure and workings of ion channels, which transport ions through cell walls and allow cells to generate and transmit electrical signals.

Did Engineers come close to replicate Nature? – No. Is it not a life-time motivation to be a membrane scientist?

My life voyage in Membranes so far (2021).

1993	2001	2010	2021
Russia Membrane Gas Separation **M.Sci**	South Africa Membrane Gas Absorption **PhD (Stellenboch)** **Y FRD rating**	Canada Membranes for Fuel Cells & Industrial Water Treatment & Osmotic Membrane Distillation **2 USA patents**	South Africa Membranes for Hydrogen Production & Compression **C1 NRF rating,** **HySA R250 mln +**

2000



Oscar Wilde:
"Memory is the diary we all carry about with us."

Departement Chemie
Universiteit Stellenbosch

CHEMIE B134

INLIGTINGSTUK 1998

Chemie B134 is (ewenàs alle ander chemie kursusse vir die eerstejaars) 'n semestervak wat saamgestel is vir B.Sc. studente in die landbouwetenskappe, bosbou, biologiese en huishoudelike wetenskappe wat van voorneme is om Chemie slegs op eerstejaarsvlak te volg. Daar word wel voorsiening gemaak vir studente wat Chemie B134 en Chemie 154 slaag en 'n bevredigende studierekord het, om Chemie op tweedejaarsvlak te neem. Chemie 114 en 154 is die enigste kursusse wat direkte toelating tot Chemie 2 verseker.

1. **Departementele Voorsitter:**

Prof B.V. Burger
Kamer 2027B
De Beersgebou
Tel: (808) 3328

2. **Dosente:**

Dr H.J. Adendorff
Kamer 2003
Gebou vir Anorganiese Chemie
Tel: (808) 3350

Dr D.G. Bessarabov
Kamer 2004
Instituut vir polimeerwetenskap
Tel: (808) 3169
808 3367

1

SUID-AFRIKAANSE TYDSKRIF VIR
CHEMIESE INGENIEURSWESE

SOUTH AFRICAN JOURNAL OF
CHEMICAL ENGINEERING

Vol 6 No 2 Oktober / October 1994

INHOUDSOPGAWE / CONTENTS

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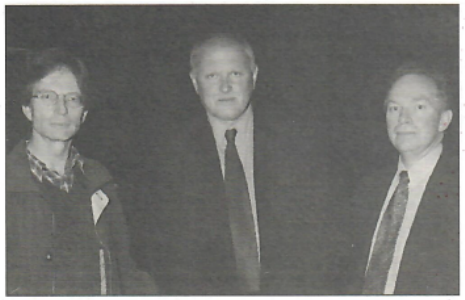


Bekende Kroaat gee lesing

PROF STANISLAV TUKSAR (middel), hoogleraar in Musiekwetenskap aan die Universiteit van Zagreb in Kroasië, en mederedakteur van die tydskrif, *International Review of the Aesthetics and Sociology of Music*, is hier afgeneem tydens sy besoek aan die Konservatorium waar hy 'n lesing met die titel, *Ten Centuries of Croatian Musical Culture* gelewer het. Hy het ook lesings aan die Universiteite van Natal, Wits en Pretoria gelewer. Sy besoek hier was op uitnodiging van die Departement Musiek en is moontlik gemaak deur dr Winfried Lüdemann (links), dosent in Musiekwetenskap, Departement Musiek. Regs is prof Hans Roosenschoon, direkteur van die Konservatorium en voorsitter van die Departement Musiek.

Lecturer wins bronze medal

Dr Dmitri Bessarabov

DR DMITRI BESSARABOV (32), senior lecturer in the Department of Chemistry, recently won a bronze medal at the South African National Okinawan Goju Ryu Karate Championship which took place in Bloemfontein. Okinawan Goju Ryu karate is a traditional style of karate with roots in China. Dr Bessarabov moved to South Africa from Russia six years ago. He obtained a PhD (Polymer Science) from Stellenbosch in 1996, for which he was awarded a SASOL postgraduate medal by the SA Chemical Institute. He has published over 70 various papers in the field of physical chemistry of membrane processes and received an "Y" rating from the NRF last year.

Vakature Vacancy

♦ IN DIE DEPARTEMENT DIDAKTIEK - VIR 'N EERSTE DEPARTEMENTELE BEAMPTE. Pligte: organisasie en administrasie van Onderwyspraktyk (B Prim en HOD); skakeling met skole en vakdidiktiekdosente i.v.m. onderwyspraktyk; ander departementele administratiewe take soos opgedra. Vereistes: goeie administratiewe en interpersoonlike vaardighede; rekenaar- en tikvaardig; tweetalig en goeie kommunikasievaardighede (Afrikaans en Engels); onderwyskwalifikasie en -ervaring. Aanbevelings: kennis van en vaardig ten opsigte van Windows 95, MS Office en die US se inligtingstelsel. Diensaanvaarding: 1 Januarie 2000. Sluitingsdatum: 15 Oktober 1999. Navrae: prof Arend Carl (tel. 808-2285; e-pos: aec2@akad.sun.ac.za).

MICROHETEROGENEOUS POLYMERIC BARRIERS FOR MEMBRANE CONTACTORS : STUDY OF GAS AND VAPOUR SEPARATIONS

Bessarabov, D. G.(Dmitri Georgievich) (1996)

Dissertation (Ph. D.) -- University of Stellenbosch, 1996.

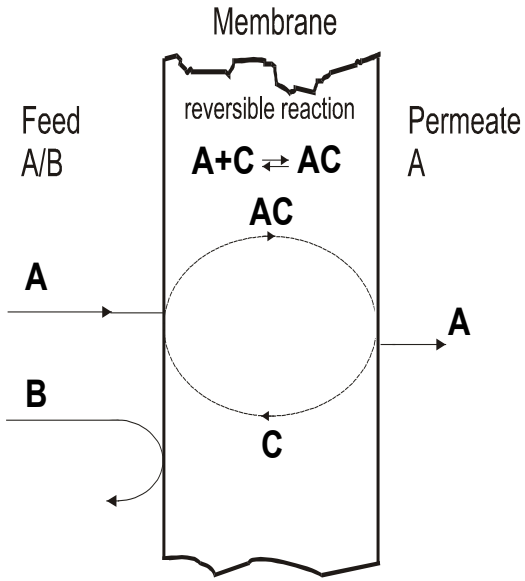
One copy microfiche.

Full text to be digitised and attached to bibliographic record.

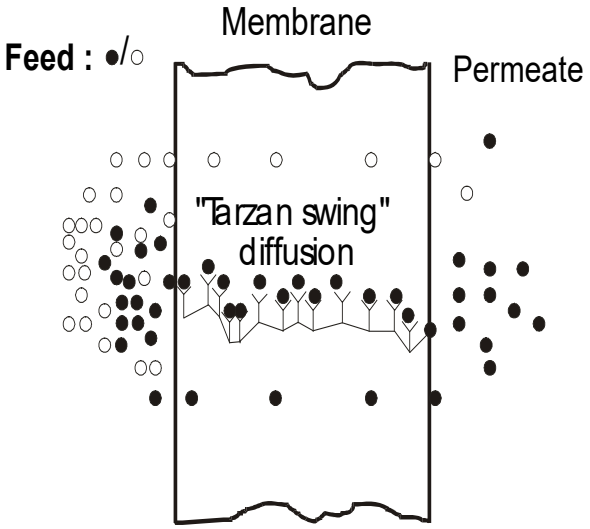
THESIS

Example of hybridization of technologies:

- **Membrane : Separation Barrier,**
- **Chemical complexation : High selectivity,**
- **Gas Liquid Absorption: High productivity**



Schematic of Immobilized Liquid Membrane (ILM)



Fixed-Site Carrier (FSC) membrane approach

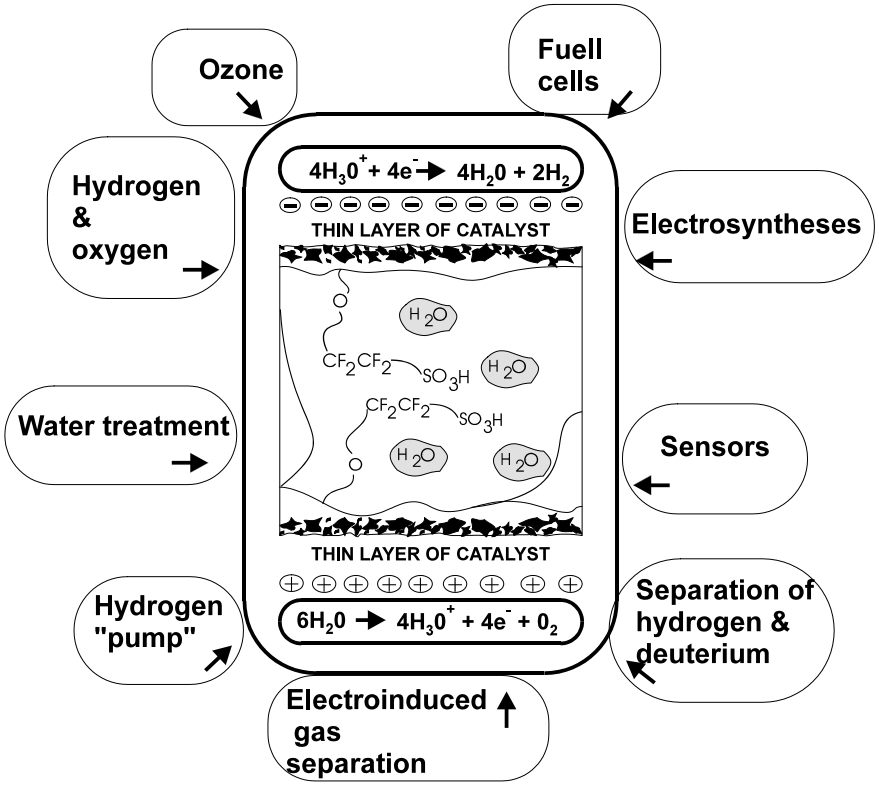
Applications of PEM technology in electro-catalysis: Academic Approach and Philosophy.

My academic philosophy:

- **Apply fundamental multidisciplinary knowledge**

(e.g., driving forces, mass transport processes, identify boundary conditions, know material properties, know characterization methods, etc),

- **Find new applications,**
- **Identify commonalities and gaps,**
- **Do not be afraid of multidisciplinary research,**
- **Be visionary**



D.G. Bessarabov, Electrochemically-aided membrane separation and catalytic Processes. Membrane Technology, Volume 1998, Issue 93, p 8 -11

https://doi.org/10.1016/S0958-2118(00)87423-6

December 2001, EU Membrane Society used the image of structured catalyst deposited on PEM membranes.

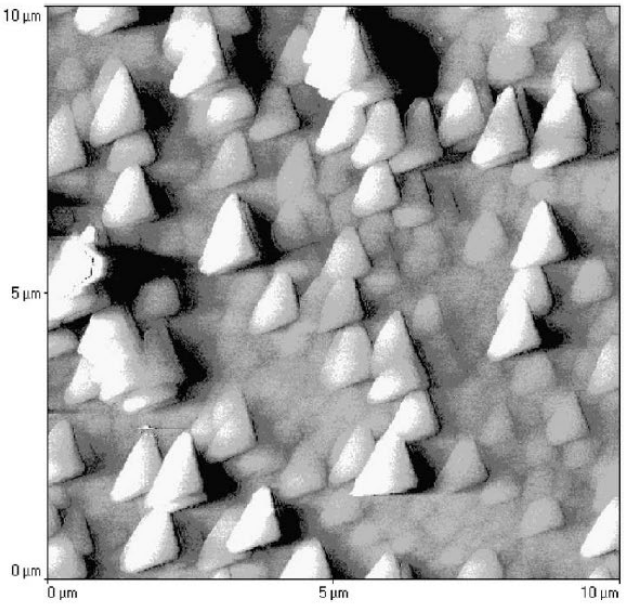
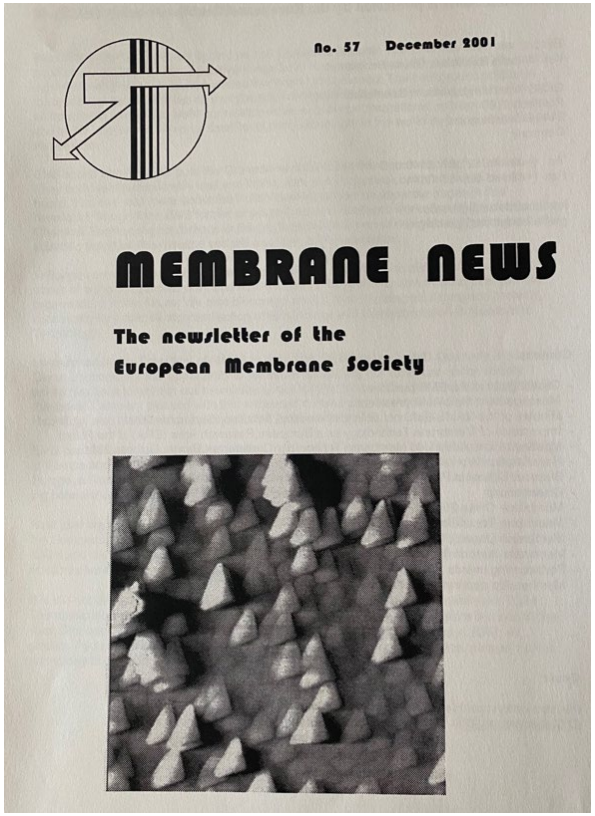


Fig. 2. Typical AFM top surface image (10 μm × 10 μm) of a platinum pyramidal-textured catalyst deposited onto the cation-exchange membrane that was modified with 1% $CH_3(CH_2)_{15}N(CH_3)_3Br$ surfactant.



Later the method was called the "Bessarabov and Michaels method"

Stellenbosch: my Membrane Voyage Continues and Moves to Electrochemistry

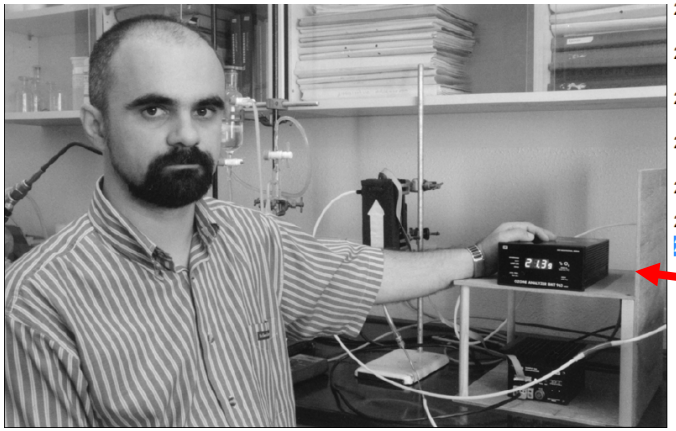
Imagination is more important than knowledge. Albert Einstein.

My academic philosophy:

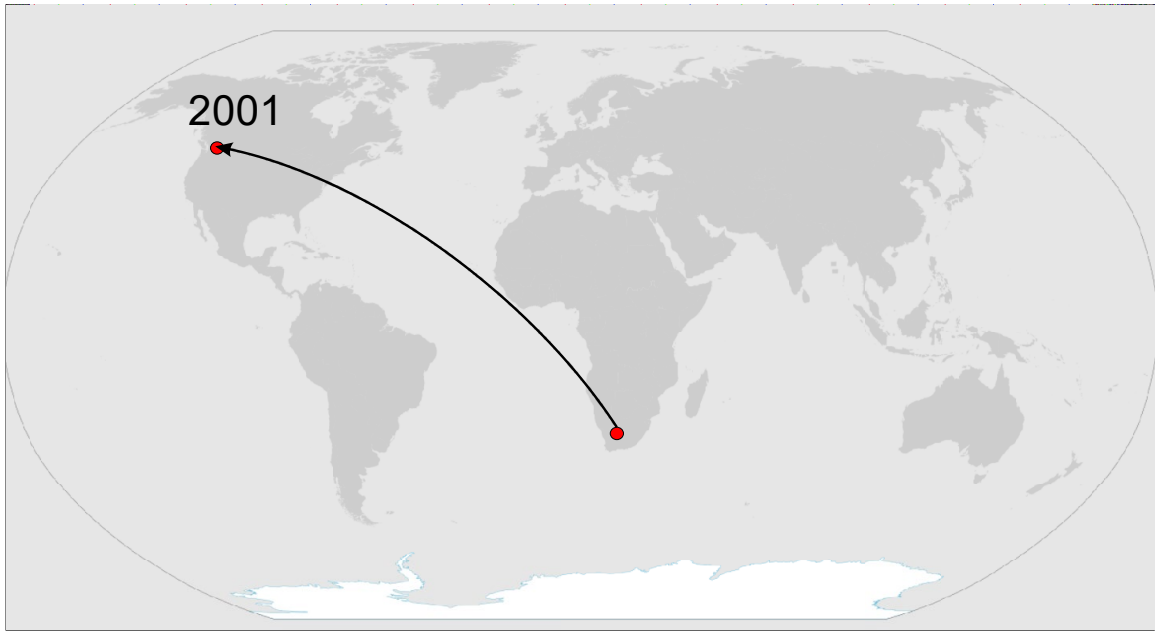
- **Identify commonalities and gaps in various technologies and be interdisciplinary !**

WRC South Africa - Membrane Technology

Year	Title	Code
2009	A Feasibility Study in e Thekwini Municipality on Anaerobic Digestion for the Treatment of Toxic and High Strength Organic Wastes: A Study of the Business Case of Treating High Strength Industrial Waste - CA Buckley, CJ Brouckaert new.	1538/1/09
2008	Development of a Membrane Pack for Immersed Membrane Bioreactors - VL Pillay, EP Jacobs. new	1369/1/08
2008	Membrane-Related Water Research Impact Assessment - Frost & Sullivan.	TT366/08
2008	Anti Scaling Studies on High $CaCO_3$ Waters in Spiral-Wrap Membrane Systems - I Goldie, M Aziz, AH Abozrida, RD Sanderson.	1593/1/08
2006	Application of Pinch Technology in Water Resource Management to Reduce Water Use and Wastewater Generation for an Area - KJ Strauss	1241/1/06
2006	Hydrophilization of Polysulphone Ultrafiltration Membranes by Polar Polymeric Solute Incorporation - EP Jacobs, SP roux, M Meinchen, AJ van Reenen, CE Morkel	1268/1/06
2006	A Desalination Guide for South African municipal Engineers - JA de Plessis, AJ Burger, CD Swartz, N Museev	TT266/06
2006	Development of Technology for the Selective Removal of Bioactive Pollutants by Ligands, Non-Covalently Immobilised on Membranes - EP Jacobs, P Swart, MW Bredenkamp, Z Allie, S Govender, L Liebenberg, L van Kralingen, WT Williams	1165/1/06
2004	The Evaluation and Design of Sludge Dewatering and Water Filtration Systems using Tubular Woven Fabric Technology - R Rajagopaul, VL Pillay	1172/1/04
2004	Evaluation of Nanofiltration for the Treatment of Rural Groundwater for Potable Use - DJ Modise, HM Krieg	1230/1/04
2003	Development of a Membrane Photobioreactor for the Study of Microcystin Production by Cyanobacteria - WD Leukes, J Strong, TC Downing	1103/1/03
2003	Preparation and Characterisation of Electrodes for the Electrochemical Conversion of Organic Pollutants in Water - MJ Hurndall, RD Sanderson	852/1/03
2003	Development of a Continuous Flow Membrane Reactor Catalysing the Solubilisation of Hydrophobic Pollutants by Rhamnolipid-Producing Bacteria - VS Brözel	846/1/03
2003	Cleaning and Pre-Treatment Techniques for Ultrafiltration Membranes Fouled by Pulp and Paper Effluent - P Swart, GS Domingo, EP Jacons, G Burch	1035/1/01
2003	A Preliminary Investigation into the Application of Ultrasonic Techniques to Membrane Filtration - RD Sanderson, Jianxin Li, DK Hallbauer, LJ Koen, V Ye Halbauer-Zadorozhanya, M Hurndall	930/1/03
2003	Treatment of Landfill Leachate from Hazardous and Municipal Solid Waste - JJ Schoeman, A Steyn, JL Slabbert, EA Venter	1167/1/03
2002	Electrochemical Generation of High-Concentration Ozone in Compact Integrated Membrane Systems - DG Bessarabov	1071/1/02

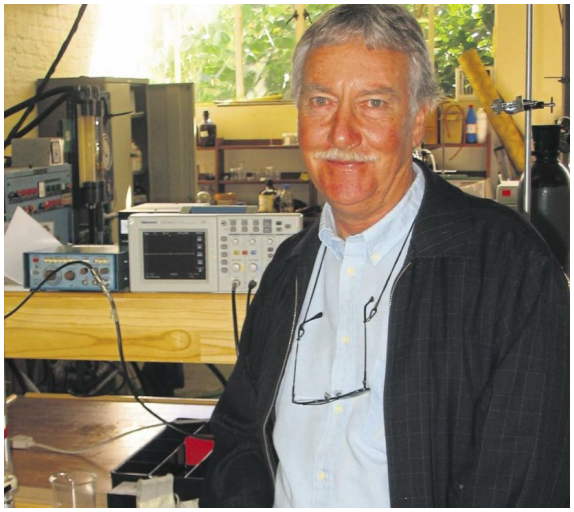


21.3% Ozone in Oxygen



9/11 2001

https://www.dailysabah.com/gallery/911-images-of-the-worst-terrorist-attack-on-us-soil/images?gallery_image=19131#big



Prof Ron Sanderson (August 2015)

https://www.netwerk24.com/netwerk24/Nuus/Baanbreker-van-US-sterf-tuis-20150813

“There's nowhere you can be that isn't where you're meant to be...”

— John Lennon

Membranes….It all starts here !

ICOM'08, 12-18 July 2008, Honolulu, Hawaii

Taking us 20 years back …

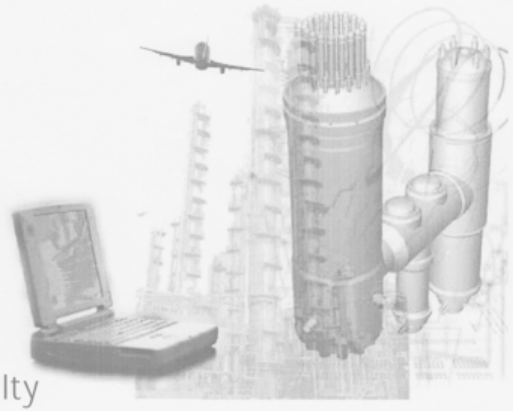
PUK Ingenieurs

Desember 2001

Potchefstroomse Universiteit vir Christelike Hoër Onderwys

Ingenieursnuus · Fakulteit Ingenieurswese Desember 2001 Uitgawe Nr.5

INHOUDSOPGAWE:



Engineering Faculty receives Diamond Arrow

The Faculty of Engineering at the Potchefstroom University for Christian Higher Education was recently honoured by the leading business magazine Professional Management Review (PMR) with a diamond arrow for their exceptional performance in the training of engineering students.

Prof Gideon Greyvenstein, the dean of the Faculty, received the award during the recent official opening of the newly equipped School for Electrical and Electronic Engineering at the PUK.

Mr Carl Wiepener, who made the award on behalf of PMR, congratulated the PUK on their exceptional achievement and pointed out that the Faculty's good reputation, status and image, as well as their contribution to the engineering industry in general and the high standard of training of students in particular, are confirmed and recognised by this award.

PMR annually undertakes investigations into the status of engineering training at tertiary institutions countrywide. In this year's evaluation the lecturers' involvement in research and development programmes in partnership with the engineering industry and other industries, and the relevance of their research results for the industry was considered. A faculty's knowledge of the worldwide engineering environment, technological environment and innovation, as well as the value addition it contributes to the South African engineering industry, were also taken into account during the evaluation and investigation. For the assessment and the investigation the magazine makes use of various companies which employ a large number of engineers, and also of consulting engineering companies. The investigation is done in the form of a comprehensive questionnaire.

At this occasion, which was also attended by the PUK's management committee, the dean expressed his gratitude and appreciation towards the principal, Prof Cornels Reinecke, for his assistance, interest and contribution in the development of the Faculty during his term as principal of the PUK.

Prof Greyvenstein expressed his appreciation for the way in which the management of the PUK over the past year created a favourable climate in which the Faculty could grow and expand, also with regard to student numbers and research. That contribution further includes the support of staff who are involved in Eskom's PBMR nuclear power project, the construction of a new building for Instrument Making and the establishment of the Centre for Research and Commercialisation under the leadership of Prof Eddie Mathews, as well as the recent implementation of the post of Vice-Principal Technology.

Recent achievements of the Faculty include large financial support from the industry for research projects in the Faculty, and the recent successful accreditation visit by ECSA (the Engineering Council of South Africa).

Mr Carl Wiepener (left) hands the award to Prof Gideon Greyvenstein, dean of the Faculty of Engineering.

Some of the development for this measuring system was done by past graduate students as their final year projects. These students had the opportunity to help develop a sophisticated measuring system, and were exposed to hardware and software development. Because of the development of the microcontrollers and peripherals, current graduate students can now use the apparatus for their projects.

A measuring system for 10 measuring points is near completion. Some hardware testing still needs to be done, as well as some code development. The system is due for completion at the end of the current year, and will be used for research. This measuring system can be applied in many branches of engineering where measurements are required.

For any further detail please contact D W Ackermann at eeldwa@puknet.puk.ac.za or X1944.

Dekaan vir verdere vier jaar benoem

Die termyn van die dekaan, prof Gideon Greyvenstein, verstryk op 31 Desember 2001. Tydens 'n vergadering van die Fakulteitsraad Ingenieurswese op 26 Oktober vanjaar is eenparig aanbeveel dat hy vir 'n verdere termyn van vier jaar benoem word. Hierdie aanbeveling is deur die Senaat van die Universiteit goedgekeur.

Prof Greyvenstein het die Fakulteitsraad en kollegas bedank vir die vertroue in hom gestel en met dank en waardering teenoor sy kollegas die feit beklemtoon dat die volgehoue groei en sukses van die Fakulteit 'n spanpoging is. Hy het veral ook sy dank en waardering teenoor kollegas van die Fakulteit Natuurwetenskappe uitgespreek, wat 'n groot en belangrike aandeel in die opleiding van ingenieurstudente het.

Prof Greyvenstein is tans baie betrokke by belangrike strategiese navorsing en projekte (onder meer veral ook die Eskom kernkrag PBMR-projek) en hy het studieverlof vir die eerste ses maande van 2002 ontvang. In die lig van sy afwesigheid is prof Schalk Vorster van die Skool vir Chemiese en Mineraalingenieurswese as waarnemende dekaan benoem.

Prof Dolf Bruinsma

Mnr Jan Kroeze

Prof Jan de Kock

Prof Albert Helberg

Agt nuwe personeellede is vanjaar in die Fakulteit Ingenieurswese aangestel. Hierdie aanstellings versterk die bestaande personeelkorps wat die opleidingsfunksie (veral wat die groeiende getal studente binne die Skool vir Elektriese en Elektroniese Ingenieurswese betref) en is 'n groot aanwins vir die kundigheid en mannekrag wat die bevordering van navorsing binne die Fakulteit ten goede sal steun.

Prof Dolf Bruinsma is vanaf Januarie 2001 as die direkteur van die fokusarea Skeidingswetenskappe en Tegnologie, asook as die direkteur van die Sasol Sentrum vir Skeidingstegnologie aangestel. Die Skool vir Chemiese en Mineraalingenieurswese se navorsingsfokus sluit nou aan by die van die fokusarea Skeidingswetenskappe en Tegnologie en prof Bruinsma doseer ook vakke binne die skool. Hy is in Blokker, Nederland gebore en het sy Ph.D. aan die universiteit van Amsterdam verwerf. Sy navorsingspesialiseringsrigting is Skeidingsprosesse (Kristallisering en Presipitering) en hy was voor sy PUK-aanstelling aan die Universiteit van Delft as medeprofessor werksaam. Hy is getroud met me. Paula de Haan.

Mnr Jan Kroeze is vanjaar as tegnikus by die Skool vir Chemiese en Mineraalingenieurswese aangestel. Hy is 'n oud-Potchefstromer en was voor sy PUK-aanstelling by Lectron Systems werksaam. Jan en Petro is die trotse ouers van 'n seun, Willem (11) en twee dogters, Wieki (12) en Jandré (1).

Prof Jan de Kock is in Mei vanjaar as professor en programleier vir Elektriese Ingenieurswese in die Skool vir Elektriese en Elektroniese Ingenieurswese aangestel. Sy navorsingspesialiseringsrigting is Kragstelsels. Jan het in Natal en Port Elizabeth grootgeword en sy kwalifikasies aan die Universiteit van Stellenbosch verwerf. Hy was as ingenieur by Sasol (1992 tot 1995) en vanaf 1997 by NETGroup werksaam. Jan en sy vrou, Elma, is die trotse ouers van Hanke (5) en Imke (3).

Prof Albert Helberg is as professor in die Skool vir Elektriese en Elektroniese Ingenieurswese aangestel, veral met die uitdaging om die nuwe rigting Rekenaaringenieurswese te help uitbou. Hy het sy Ph.D. in ingenieurswese in 1993 by RAU verwerf en was voorheen by Eskom Nasionale Telekommunikasie en PQAfrica (PQNetworks) werksaam. Sy navorsingsbelangstellings sluit Telekommunikasie, Telekommunikasie Netwerkbestuur en Inligtingsekerheid in. Albert en Louise is die trotse ouers van klein Victor (2).

Mnr Rodney Tessendorf

Mnr Manfred Trumpelmann

Prof George van Schoor

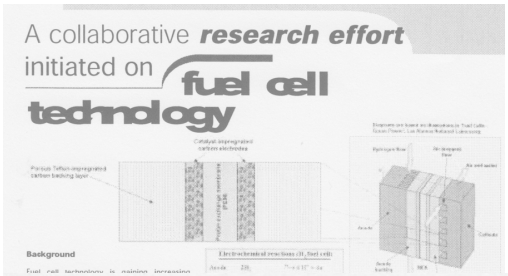
Mnr Jacobus Vermeulen

Mnr Rodney Tessendorf is 'n oudstudent van die PUK, wat in 1998 sy B.Ing.-graad met lof voltooi het. Hy was voor sy aanstelling as lektor in die Skool vir Elektriese en Elektroniese Ingenieurswese by Grintek Electronics werksaam. Hy voltooi binnekort sy M.Ing. en sy spesialiseringsrigting is Elektriese Stelsels en Elektrodegniek. Rodney is in Sluiterheim in die Oos-Kaap gebore en het ook daar grootgeword.

Mnr Manfred Trumpelmann is vanjaar as senior tegnikus by die Skool vir Elektriese en Elektroniese Ingenieurswese aangestel. Hy is 'n oud-Pretorianer wat in Centurion grootgeword en sy kwalifikasies by die Pretoria Technikon verwerf het. Hy was by die AEK in Pelindaba as 'n elektroniese tegnikus in verskeie departemente vir 'n tydperk van 27 jaar werksaam. Vanaf 1998 het hy as vrystaat elektroniese konsultant gewerk tot sy aanstelling by die PUK vroeër vanjaar. Hy is die trotse pa van 'n dogter Therese (17), wat vanjaar die hoofmeisie van Bloemfontein Hoërskool is, en twee seuns, Hellmut (14) en Rudolph (12).

Prof George van Schoor is vanjaar as medeprofessor in die Skool vir Elektriese en Elektroniese Ingenieurswese aangestel. Hy het aan die RAU studeer en was voorheen vir agt jaar by Kentron werksaam. Hy was dosent by die Technikon SA voor sy aanstelling by die PUK. In sy navorsing spesialiseer hy in Moderne Beheerstelsels. Hy is getroud met Engelet ('n elektriese ingenieur) en hulle is die trotse ouers van 'n seun, Stefan (11), en dogter, Rinemarè (8).

Mnr Jacobus Vermeulen is in Januarie 2001 as senior lektor in die Skool vir Elektriese en Elektroniese Ingenieurswese aangestel. Hy doen navorsing oor Kragstelsels en Elektriese Stelsels. Sy B.Ing.-kwalifikasie het hy by die Universiteit van Pretoria verwerf en sy M.Ing. by die Vaaldriehoek Technikon. Voor sy aanstelling by die PUK was hy dosent by die Vaaldriehoek Technikon. Jacobus is getroud met Yolande en hulle is die trotse ouers van Yeshua (2) en Michelle (1).



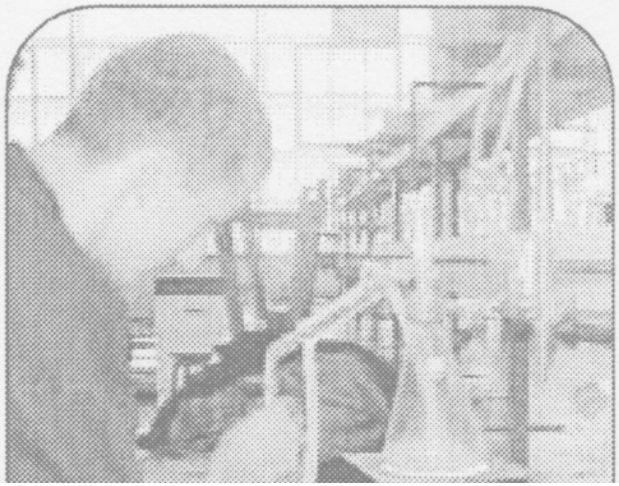
2001.....

Fuel cell research initiative at the PU for CHE

A research project was initiated in the Materials and Manufacturing research group at the start of 2001 on the characterization of novel PEM fuel cell membranes. The research group at the PU for CHE working on the fuel cell project currently consists of Dr Berni Jooste (Chemical & Minerals Engineering), Prof Johan Markgraaff (Mechanical & Materials Engineering) and Peter Mukoma (a masters degree student in Chemical & Minerals Engineering). Prof Manie Vosloo (Chemistry & Biochemistry) of the SASOL Separations Science and Technology (SST) research group, who is an experienced researcher in polymer synthesis and characterization, is also actively participating in the fuel cell project. This project will initially focus on the characterization of new materials for PEMs intended for fuel cells. Later research will also address the development and evaluation of new membranes as well as evaluation of new membranes under fuel cell conditions. The project was initiated after a co-operative agreement was made with Dr Stuart Schwab of Thor Technologies Inc. (USA) and Dr Larry Kepley of Electrophorics Inc. (USA) who are both involved in the development of novel PEM membranes based on dendritic polymer (dendrimer) chemistry. There is also interest from Dr Dmitri Bessarabov of the Department of Chemistry, University of Stellenbosch (who is developing modified Nafion PEMs) to co-operate with our research group. It is our goal to characterize new PEM membranes in co-operation with the developers to gain an understanding of the important parameters in the development of a fuel cell membrane material and to build a knowledge base at the PU for CHE on fuel cells and fuel cell materials.

http://www.puk.ac.za/engineering/index.html

Ingenieurskool
vir
hoërskoolleerlinge



Canadian Membrane "Journey" begins. 2001. Hydrogen was one of the key issues.

Exciting industrial R&D around boring NaCl, Na_2SO_4 and NaOH.

$$2NaCl + 2H_2O \rightarrow Cl_2 + H_2 + 2NaOH$$

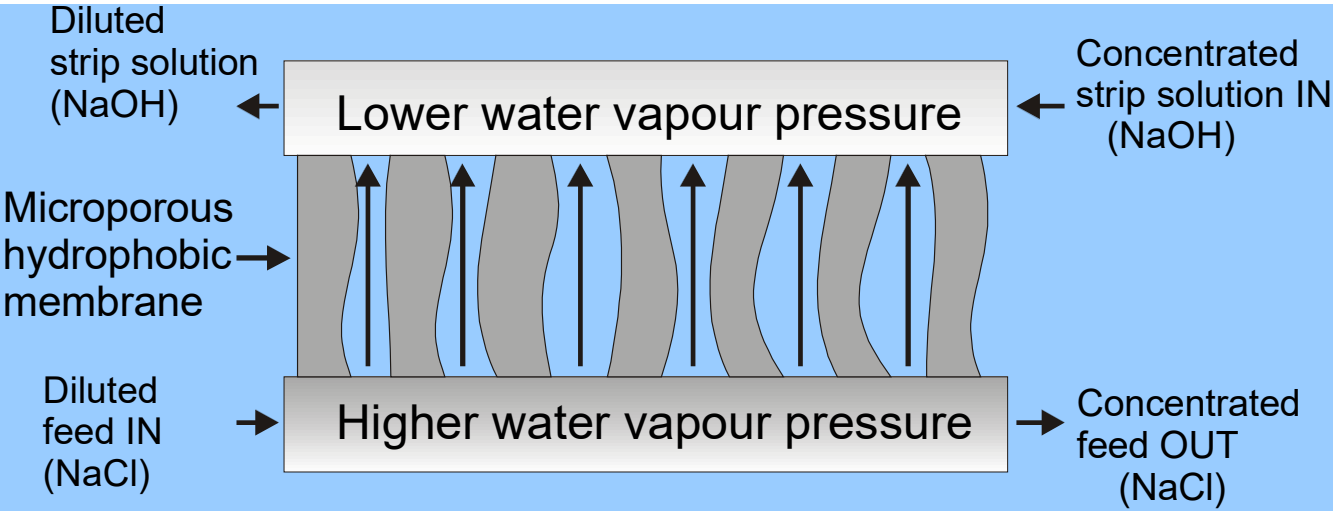
This simple reaction of brine electrolysis is a multi-billon dollar business

For most people, the chlor-alkali process is most closely associated with the odor of clean pools. But the chlor-alkali process is so much bigger than that: It is part of a well-established market, one of the world's largest chemical processing industries, and is poised for continued growth. The global Chlor-Alkali market size is estimated to be USD 63.2 billion in 2021 and is projected to reach USD 77.4 billion by 2026, at a CAGR of 4.1% between 2021 and 2026.

https://www.marketsandmarkets.com/Market-Reports/chlor-alkali-market-708.html?gclid=CjwKCAjwqeWKBhBFEiwABo_XBhAGMmz7Az1ksHj0VqcusUQTeyAFiagmUrSH_sN8lyuvFLs735-ERhoCSw0QAvD_BwE

My academic philosophy (in industry):

- Know gaps in industrial processes.
- Know what customers want !



Osmotic Membrane Distillation: APPARATUS AND METHOD FOR OSMOTIC MEMBRANE DISTILLATION
Patent date Issued Apr 22, 2008, US 7,361,276

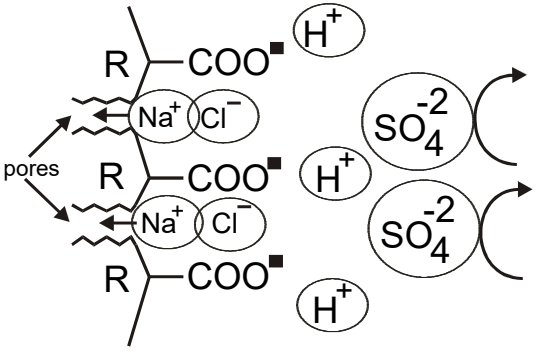
OMD involves:

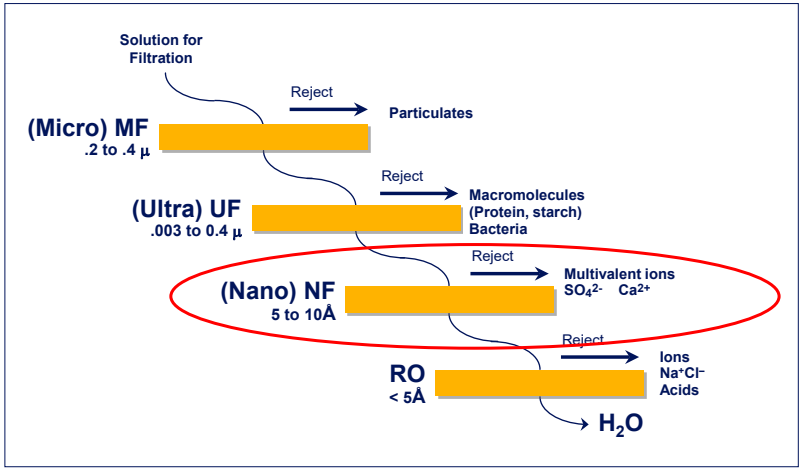
• water evaporation from the feed; water vapour diffusion through the membrane; water vapour condensation into stripping solution; **ISOTHERMAL** – No external heat input

Canadian Membrane "Journey" Continues. Nano Filtration. Industrial Water Streams.

Know your Fundamentals (driving forces, mass transport) and do not be afraid of multidisciplinary research.

schematic of membrane pores





My membrane "toys" get bigger and bigger ☺

Canadian Membrane "Journey" Continues. Membranes for Hydrogen Applications. OEMs and Fuel Cells.

- **System vs. Membranes trade-offs**
  - **Membrane advancements enable system capability**
  - **Trade-off between system and membrane needs must be achieved**

MEMBRANE ELECTRODE ASSEMBLY COMPRISING A CATALYST MIGRATION BARRIER LAYER

Patent date Issued Jul 19, 2016 Patent number US 9,397,357 B2

My academic philosophy

- **Apply fundamentals**

(e.g., driving forces, mass transport processes, identify boundary conditions, know material properties, know characterization methods, etc),

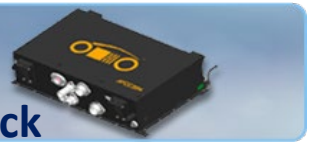
Life is not only work…

Requirements: Capability Flow

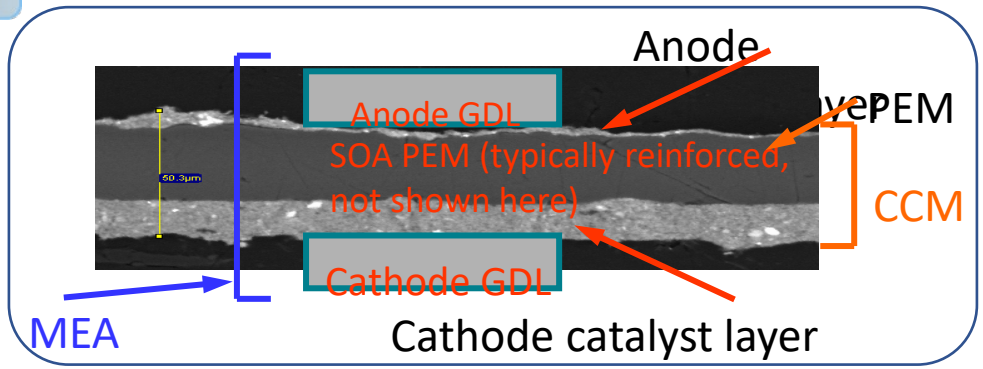
System — $x3/Kw – to motor output

FC Power Module — $x2/Kw

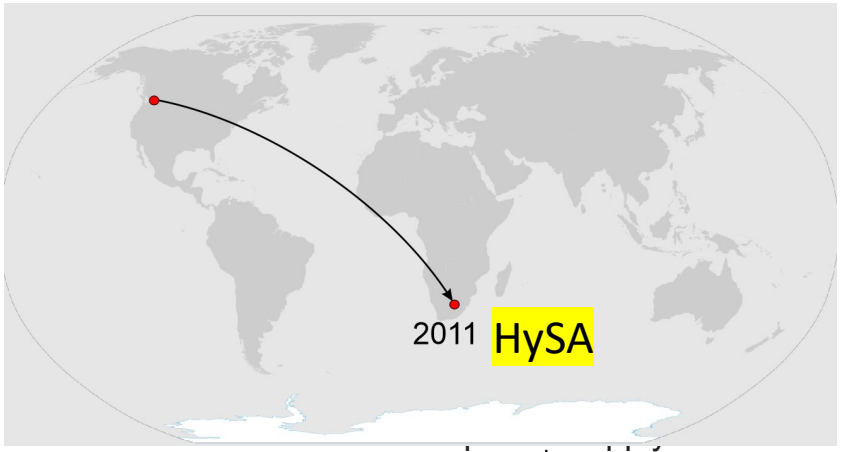
Stack — $x1/Kw

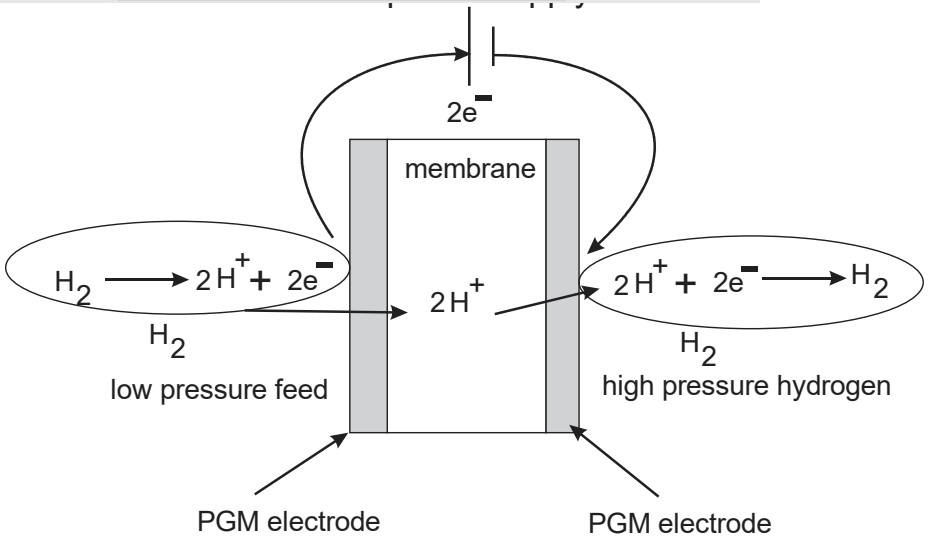


Components: (M., Cat., Diff. m., Plates, Seals, etc.)

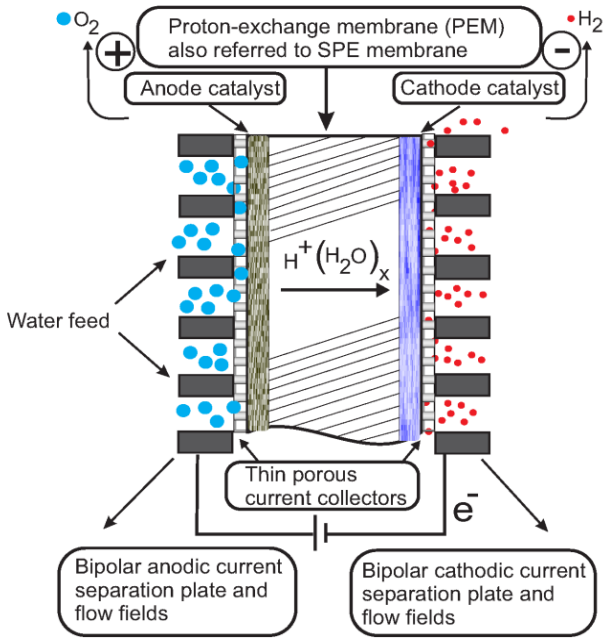


Membrane "Journey" Continues. Membranes for Hydrogen Applications. 2011. Hydrogen Compression and Generation (PEM and AEM).





$$H_2O \longrightarrow 2H^+ + \frac{1}{2}O_2(gas) + 2e^- \qquad 2H^+ + 2e^- \longrightarrow H_2(gas)$$



PEM. What Type of Membranes these are? (proton-exchange membranes)

- PEM-based system designs are largely determined by the membrane mechanical properties (Young's modulus, SOA 100 MPa and up, depending on RH% and T°), gas permeation properties, (SOA around 20 Barrer, depend on RH% and T°), IR drop (SOA Nafion 117), IEC – vs. Discharge pressure of hydrogen, operating current density and durability in PEM electrolyzers.
- Membrane advancements enable system capability. Trade-off between system and membrane needs must be achieved.

Initial investments in PEM technology were not done by hydrogen fuel cells OEMs !

In the 1960's and 1970's, mercury pollution made headlines worldwide, following a severe outbreak of mercury poisoning in Japan ("Minamata Disease"). Japan banned mercury use in the chlor-alkali process after the serious contamination accident at Minamata.

Pictures of Large Chlor-Alkali plants

Discovery of Nafion™

http://www.nafion.mysite.com/

“ Picture of Walther Grot holding up a film made of NAFION* This polymer is solid and inert like TEFLON*, but conducts electricity like the sulfuric acid electrolyte in your car battery”* NAFION and TEFLON are DuPont trademarks

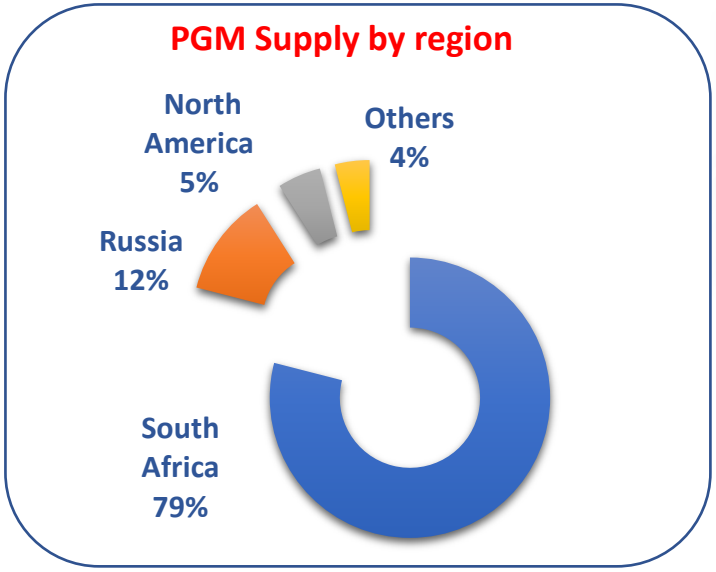
Walther Grot, the discoverer of Nafion ® at Dupont in the 1960s

1960s	1990s	2020s	2021
Nafion 117 other PFSA	Asahi Glass Asahi Kasei DOW membrane Reinforcement (W.L.Gore) Plastpolymer (Russia) Dongyue (China)	end-group stabilization Radical scavengers short-side chain (3M, Aquivion) Recombination catalyst	3M, Chemours

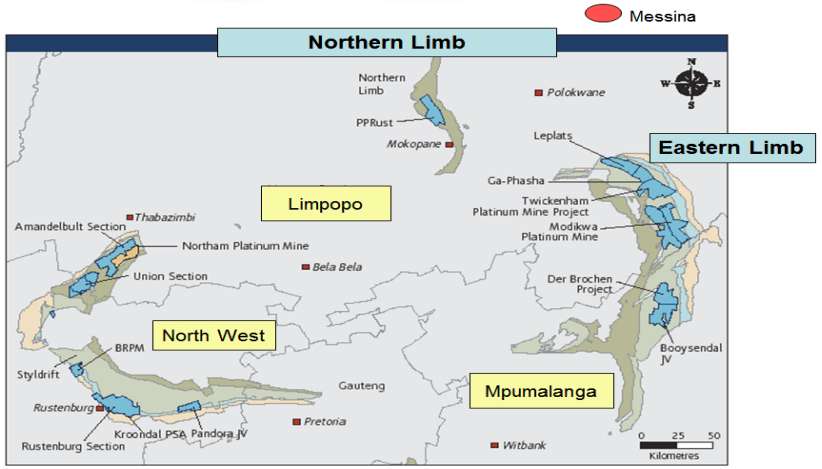
Why Hydrogen and why HySA is looking at PEM water electrolysis technology?

Glacier position in Loen, Norway, 1920

PGMs Resources in South Africa

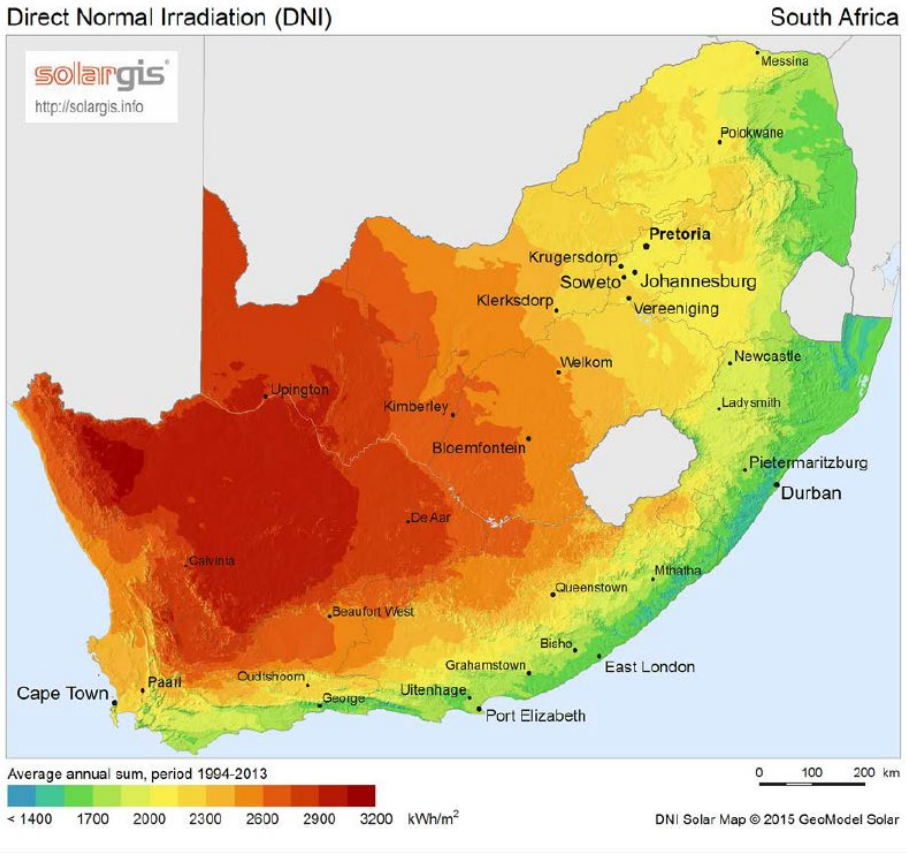


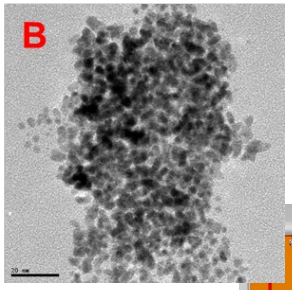
PGMs are key elements of new hydrogen technologies (e.g., hydrogen generators, compressors, hydrogen fuel cells, etc)



http://hysainfrastructure.com/

Solar Potential in SA

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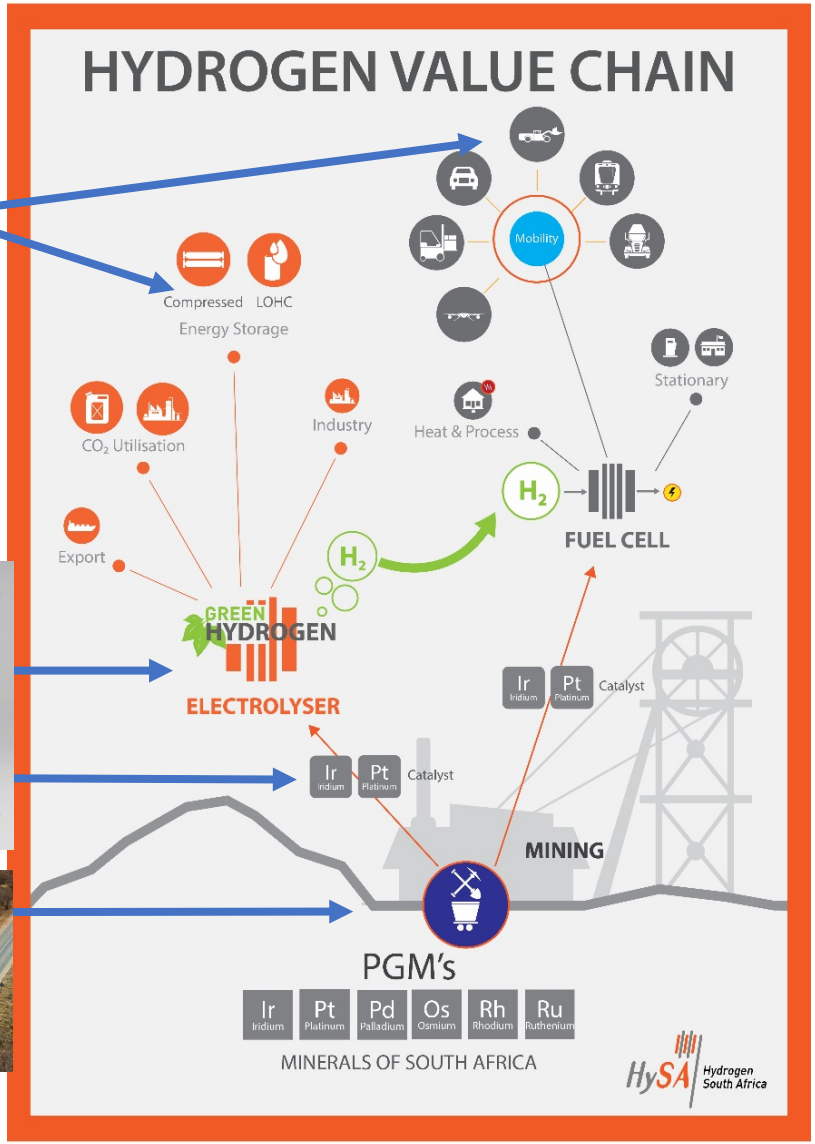
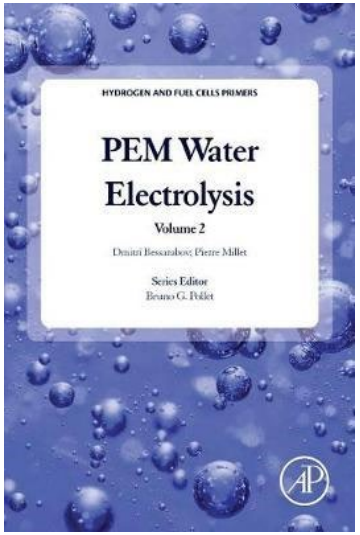
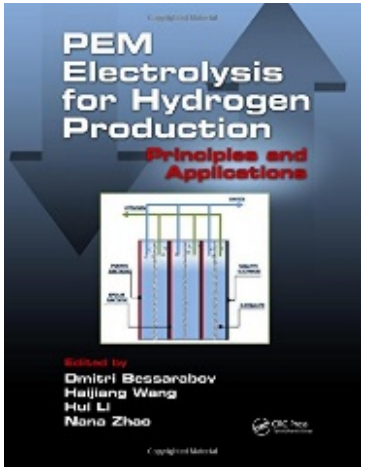
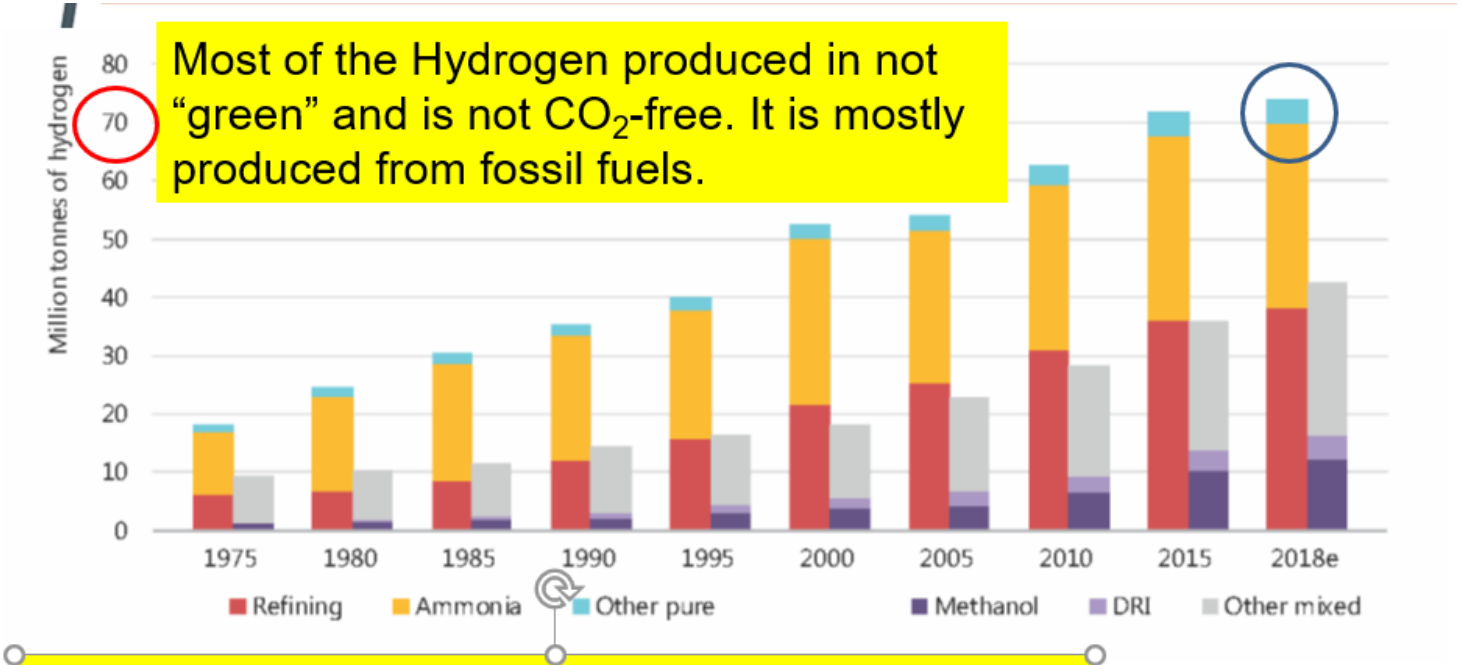

HYDROGEN VALUE CHAIN
Mobility
Compressed
LOHC
Energy Storage
Stationary
CO_2 Utilisation
Industry
Heat & Process
H_2
FUEL CELL
Export
H_2
GREEN HYDROGEN
ELECTROLYSER
Ir Iridium
Pt Platinum
Catalyst
Ir Iridium
Pt Platinum
Catalyst
MINING
PGM's
Ir Iridium
Pt Platinum
Pd Palladium
Os Osmium
Rh Rhodium
Ru Ruthenium
MINERALS OF SOUTH AFRICA
HySA Hydrogen South Africa


HYDROGEN AND FUEL CELLS PRIMERS
PEM Water Electrolysis
Volume 2
Dmitri Bessarabov, Pierre Millet
Series Editor
Bruno G. Pollet


PEM Electrolysis for Hydrogen Production
Principles and Applications
Edited by
Dmitri Bessarabov
Haijiang Wang
Hui Li
Nana Zhao

Global annual demand for hydrogen since 1975



~USD1.5 / kgH2; ~ USD 105 Billion business (if all hydrogen "changes hands") – in many cases it is consumed on site

Source: IEA, 2019

“Color” Terminology for Hydrogen

Green hydrogen

- Green hydrogen is produced by the electrolysis of water
- The process is powered by zero-carbon electricity (e.g., wind and solar power)
- It is clean, but is currently too expensive for widespread use[1]
- The cost of electrolysers and renewable energy is expected to fall over the next decade, making green hydrogen more viable
- Green hydrogen is the ideal long-term, zero-carbon way to produce hydrogen

Blue hydrogen

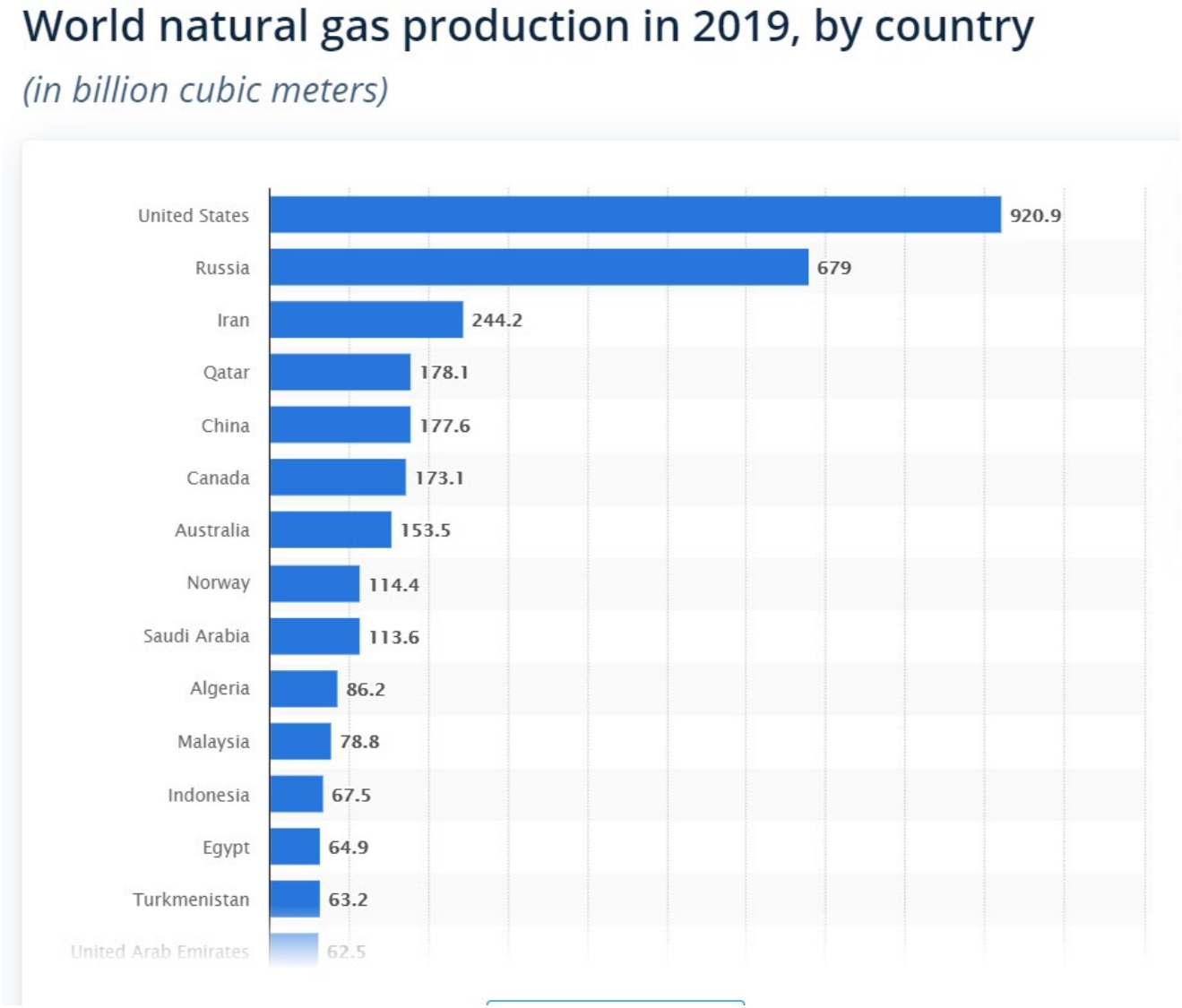
- Blue hydrogen is produced from fossil fuels (typically natural gas), but emissions are dealt with using carbon capture and storage (CCS) technology
- With abundant natural gas and coal available, blue hydrogen could help to scale the hydrogen economy[2]
- However, this is dependent on wider adoption of CCS
- Blue hydrogen could act as a stepping stone from grey/brown to green hydrogen

Grey hydrogen

- Grey hydrogen is typically produced from natural gas in a process called steam methane reformation
- Brown hydrogen is produced from the gasification of coal (or lignite)
- These are the strongly dominant methods in use today
- They are relatively cheap, but emit large amounts of CO_2

1. Path to Hydrogen Competitiveness: A Cost Perspective, Hydrogen Council: https://bit.ly/3gZqLDw
2. Unlocking the green hydrogen revolution, Recharge: https://bit.ly/35UTAuz

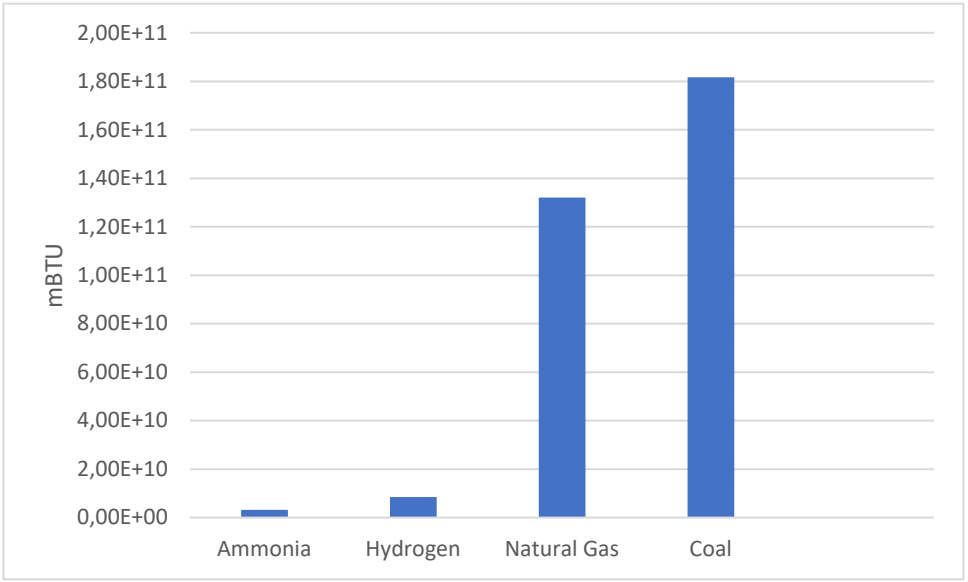
DNV report



Source: https://www.statista.com/statistics/264101/world-natural-gas-production-by-country/

Average energy content per year production (2018-2019)

Assumptions		
Natural gas density	0,68	kg/m3
Natural gas energy	40	MJ/m3
Hydrogen	120	MJ/kg
Ammonia	18,6	MJ/kg
tonne of oil equivalent	41,868	GJ
tonne of oil equivalent	39,6832072	mBTU
Natural gas energy	55	MJ/kg
Hydrogen	11	MJ/m3
Coal	23000	BTU/kg



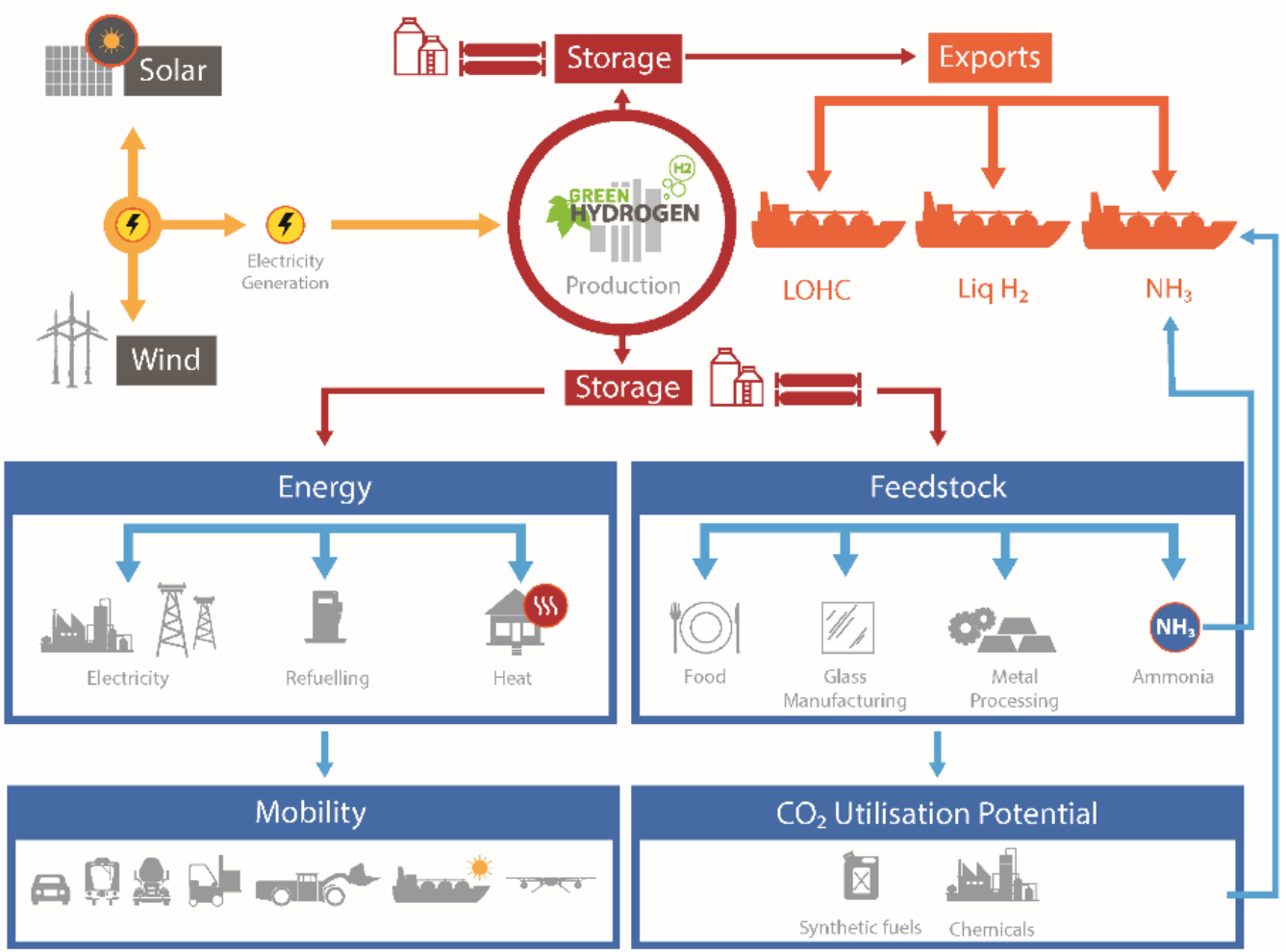
https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-natural-gas.pdf

https://www.iea.org/reports/the-future-of-hydrogen

https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf

We will need a lot more H_2 in future !

What should we be expecting in the next few decades?

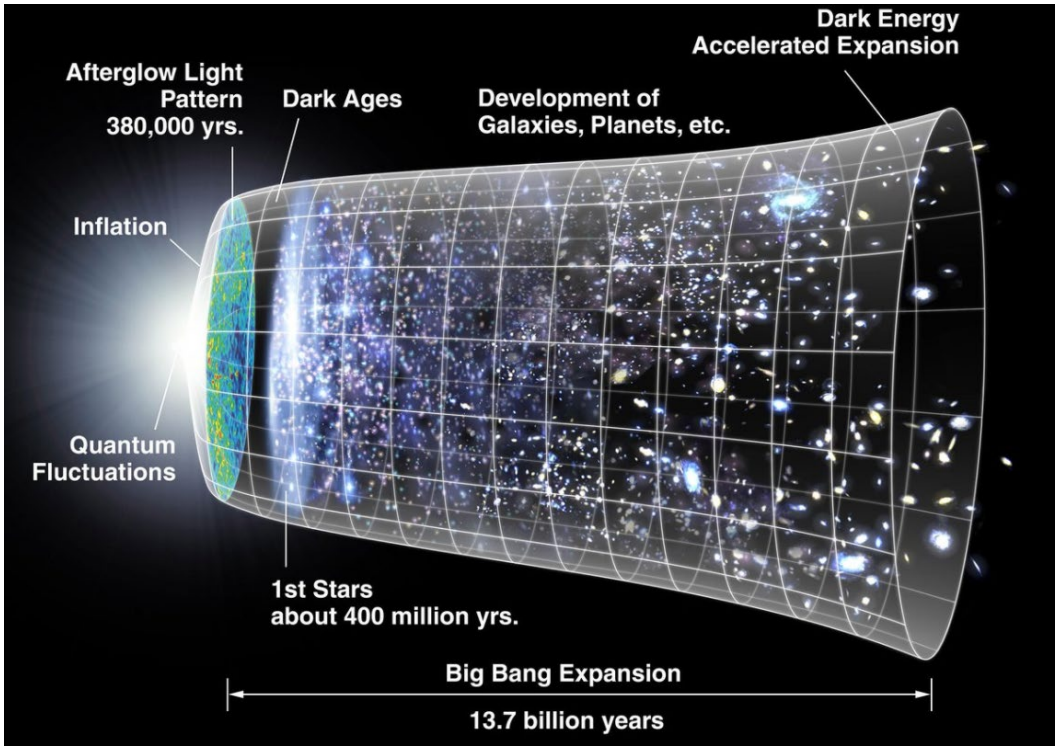


Cabinet approves extension of Hydrogen Society Roadmap

https://www.sanews.gov.za/south-africa/cabinet-approves-extension-hydrogen-society-roadmap

" Following its Special Cabinet Meeting last week, Cabinet has approved the extension of the Hydrogen Society Roadmap (HSRM) for the next 10 years.
The HSRM gives effect to the Hydrogen South Africa Strategy that was approved by Cabinet in 2007 to prepare the country for a hydrogen economy."

It all started from Hydrogen ! Modern Energy Transition moves towards Hydrogen! How long it is going to take?



https://www.jpl.nasa.gov/infographics/the-big-bang-and-expansion-of-the-universe

The Universe contains 100 billion or more galaxies, each containing billions of stars. Our Galaxy, the Milky Way, is the home of a trillion sun, many of which resemble our Sun. Each of these stars, when it is formed from an interstellar cloud, **is endowed with hydrogen and helium-simple chemical elements that formed in the Big Bang**, as well as with heavier elements that formed in previous ste1lar furnaces. Hydrogen is consumed by a thermonuclear fire in the star's core, producing heavier chemical elements that accumulate there before becoming fuel for new, higher temperature burning. In massive stars, the process continues until the element iron dominates the core.

Conclusions and going forward

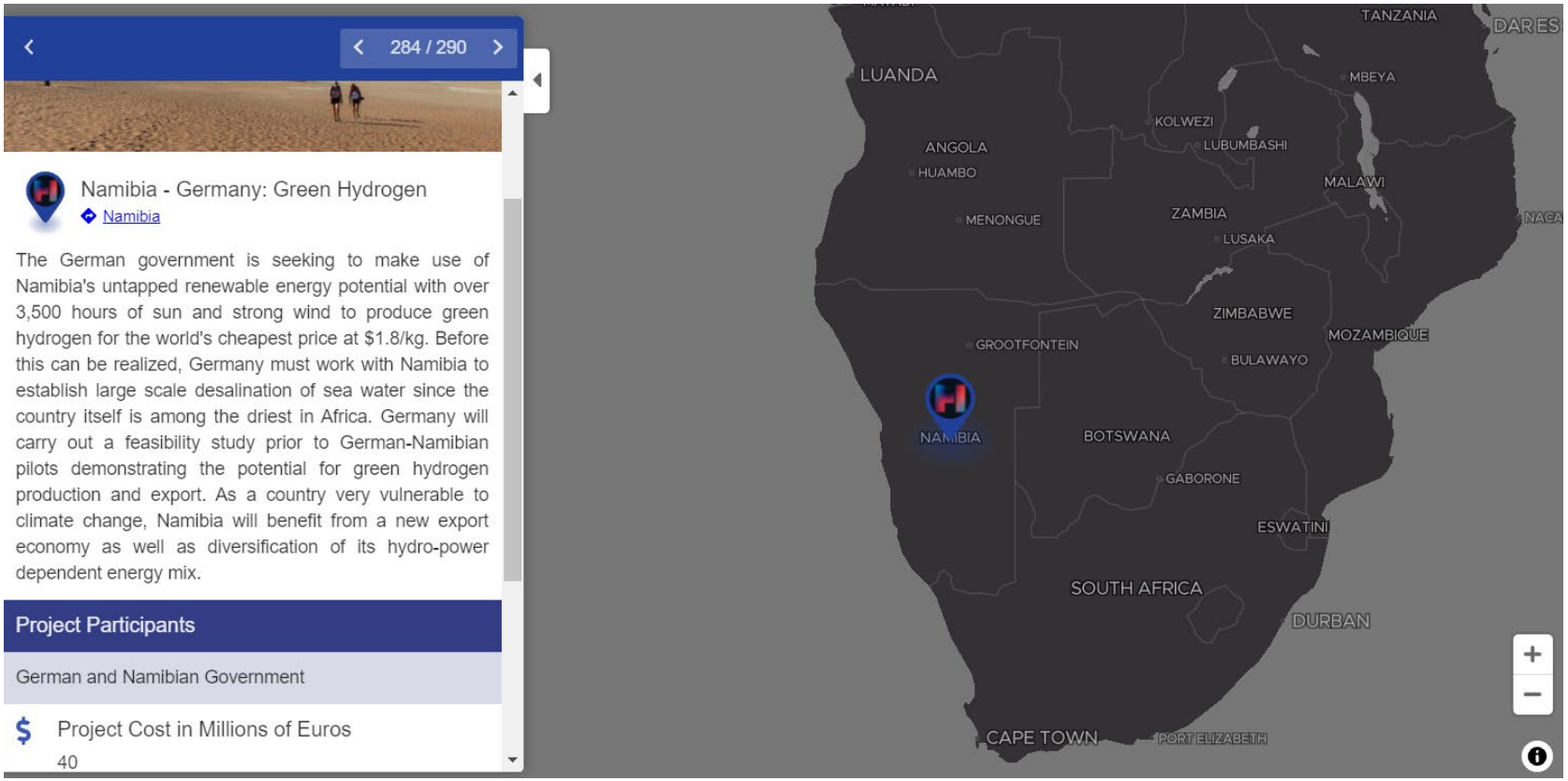
- Membranes are strongly linked to many processes including H2 production.
- I treat “Membranes” as unlimited source of innovation.
- Engineers still can not make synthetic membranes that can be as efficient as membranes in Nature.
- Unprecedented momentum for hydrogen observed internationally.
- Gigawatt scale is a target.
- HySA Centre is a leading cluster of expertise withing tertiary sector in SA.
- There will be more demand of “hydrogen” experts in SA.
- There will be more responsibility for HySA as a National Program in implementing Hydrogen Society Roadmap (HSRM)

Challenges of green H_2 implementation

- TECHNICAL CHALLENGES
- ECONOMIC CHALLENGES
- REGULATORY CHALLENGES
- SOCIAL CHALLENGES

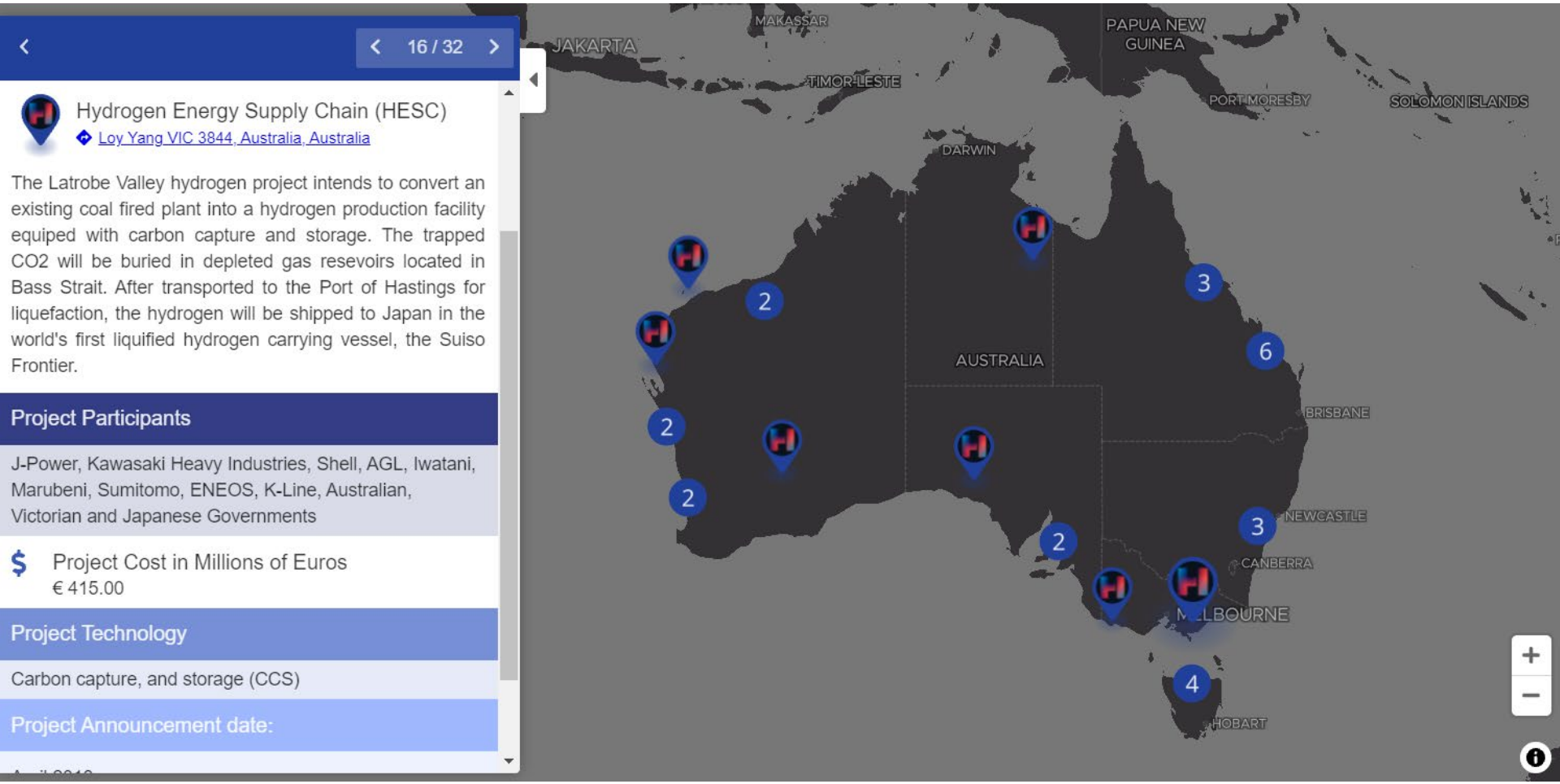
Thank you !

Recent “green” hydrogen projects next to us: Namibia



https://www.rechargenews.com/energy-transition/germany-eyes-worlds-cheapest-green-hydrogen-from-namibia-amid-global-race-for-best-sites/2-1-1057335

Australia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Hydrogen Energy Supply Chain (HESC)
Loy Yang VIC 3844, Australia, Australia
The Latrobe Valley hydrogen project intends to convert an existing coal fired plant into a hydrogen production facility equiped with carbon capture and storage. The trapped CO2 will be buried in depleted gas resevoirs located in Bass Strait. After transported to the Port of Hastings for liquefaction, the hydrogen will be shipped to Japan in the world's first liquified hydrogen carrying vessel, the Suiso Frontier.
Project Participants
J-Power, Kawasaki Heavy Industries, Shell, AGL, Iwatani, Marubeni, Sumitomo, ENEOS, K-Line, Australian, Victorian and Japanese Governments
Project Cost in Millions of Euros
€ 415.00
Project Technology
Carbon capture, and storage (CCS)
Project Announcement date:
JAKARTA
MAKASSAR
TIMOR-LESTE
PAPUA NEW GUINEA
PORT MORESBY
SOLOMON ISLANDS
DARWIN
AUSTRALIA
BRISBANE
NEWCASTLE
CANBERRA
MELBOURNE
HOBART
2
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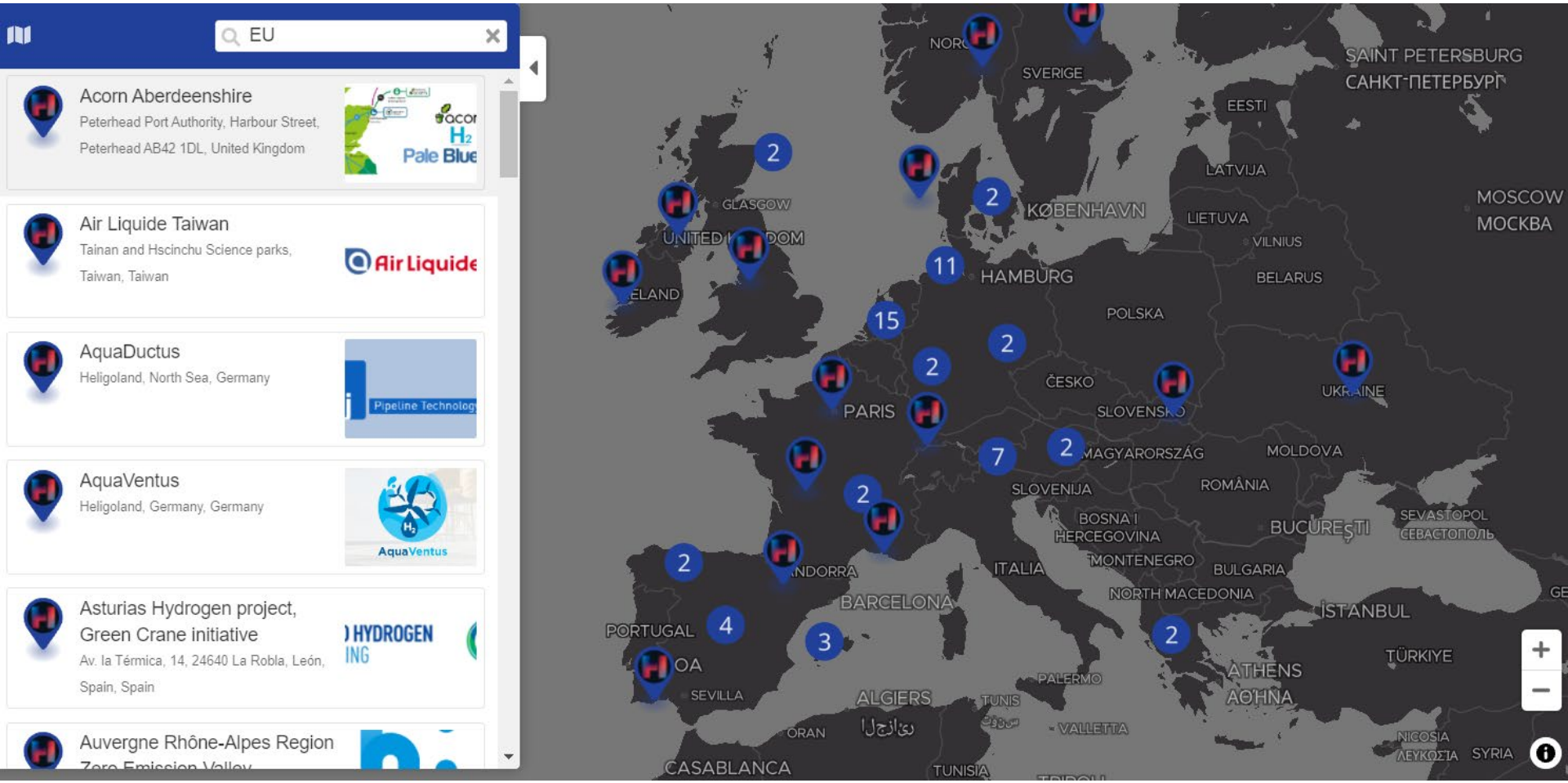
6
3
2
4

EU


EU
Acorn Aberdeenshire
Peterhead Port Authority, Harbour Street, Peterhead AB42 1DL, United Kingdom
Pale Blue
Air Liquide Taiwan
Tainan and Hscinchu Science parks, Taiwan, Taiwan
Air Liquide
AquaDuctus
Heligoland, North Sea, Germany
Pipeline Technology
AquaVentus
Heligoland, Germany, Germany
AquaVentus
Asturias Hydrogen project, Green Crane initiative
Av. la Térmica, 14, 24640 La Robla, León, Spain, Spain
HYDROGEN
Auvergne Rhône-Alpes Region
SVERIGE
SAINT PETERSBURG
САНКТ-ПЕТЕРБУРГ
EESTI
LATVIJA
KØBENHAVN
LIETUVA
VILNIUS
MOSCOW
МОСКВА
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BUCUREŞTI
SEVASTOPOL
СЕВАСТОПОЛЬ
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