Shunt-currents in Alkaline Water-Electrolyzers (AWE) and Renewable Energy

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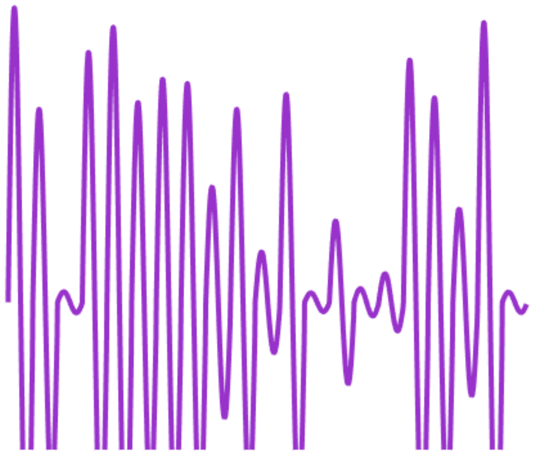
Agenda

1. Challenges
2. Shunt-currents explained
3. Energy efficiency
4. Electrode stability
5. Summary

INTRODUCTION

Challenges of high shunt-currents and renewable energy with dynamic/intermittent operation

- The challenges applies to:
  - *LARGE* AWE-stacks+high-pressure+internal manifold system
- High Specific Energy Consumption (SEC)
  - Loss in current efficiency under intermediate- and low-load operation
- Reduced lifetime
  - Corrosion and electrode stability under shut-down and deep discharge conditions
- Reduced flexibility
  - Gas-impurities and limited low-load operation
- Increased safety risk
  - Actual current density in the cells is lower and gas cross-over and lye-mixing have higher impact
  - Secondary electrolysis may compromise the gas impurity
  - +additional topics

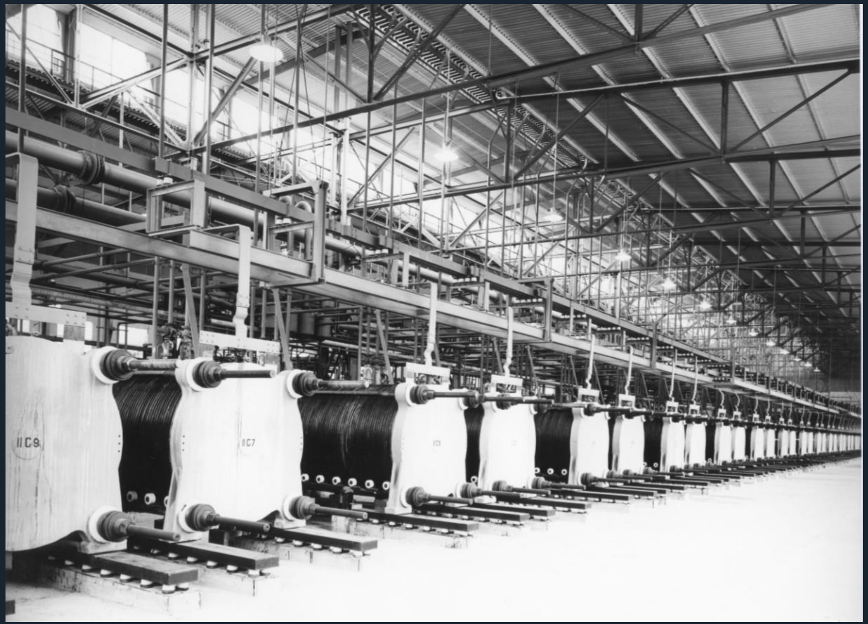


The heritage of AWE-production in Norway

1905	1929 ↔ 1991		1993	2011	2014	
	Large-scale AWE plants for fertilizer production			NEL HYDROGEN	nel Oslo Stock Exchange	
Norsk Hydro formed World leading fertilizer company	Production of AWE in NH	Electrolyser plants shut down	Norsk Hydro Electrolysers Formed as subsidiary of NH			Green hydrogen

5MW test plant, Notodden, Norway ~1928 (Holmboe-cellen, monopolar)

Norsk Hydro plant Glomfjord, Norway 1951-1991



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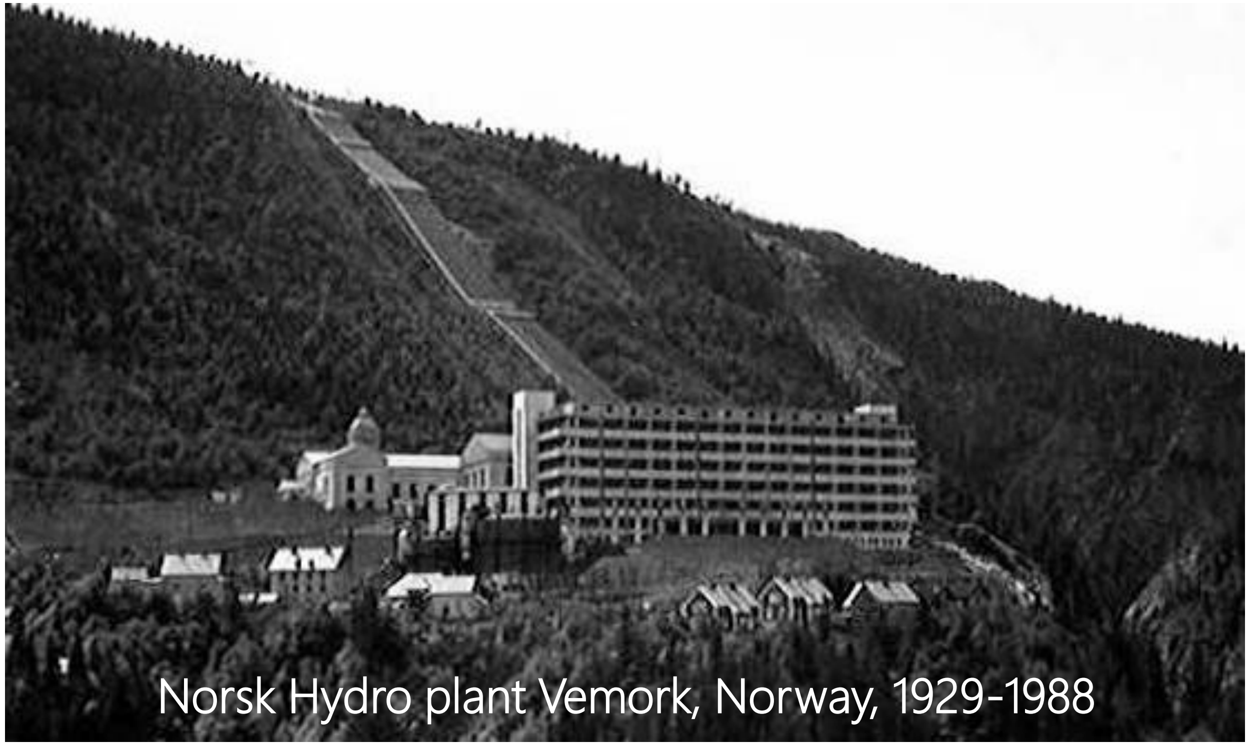
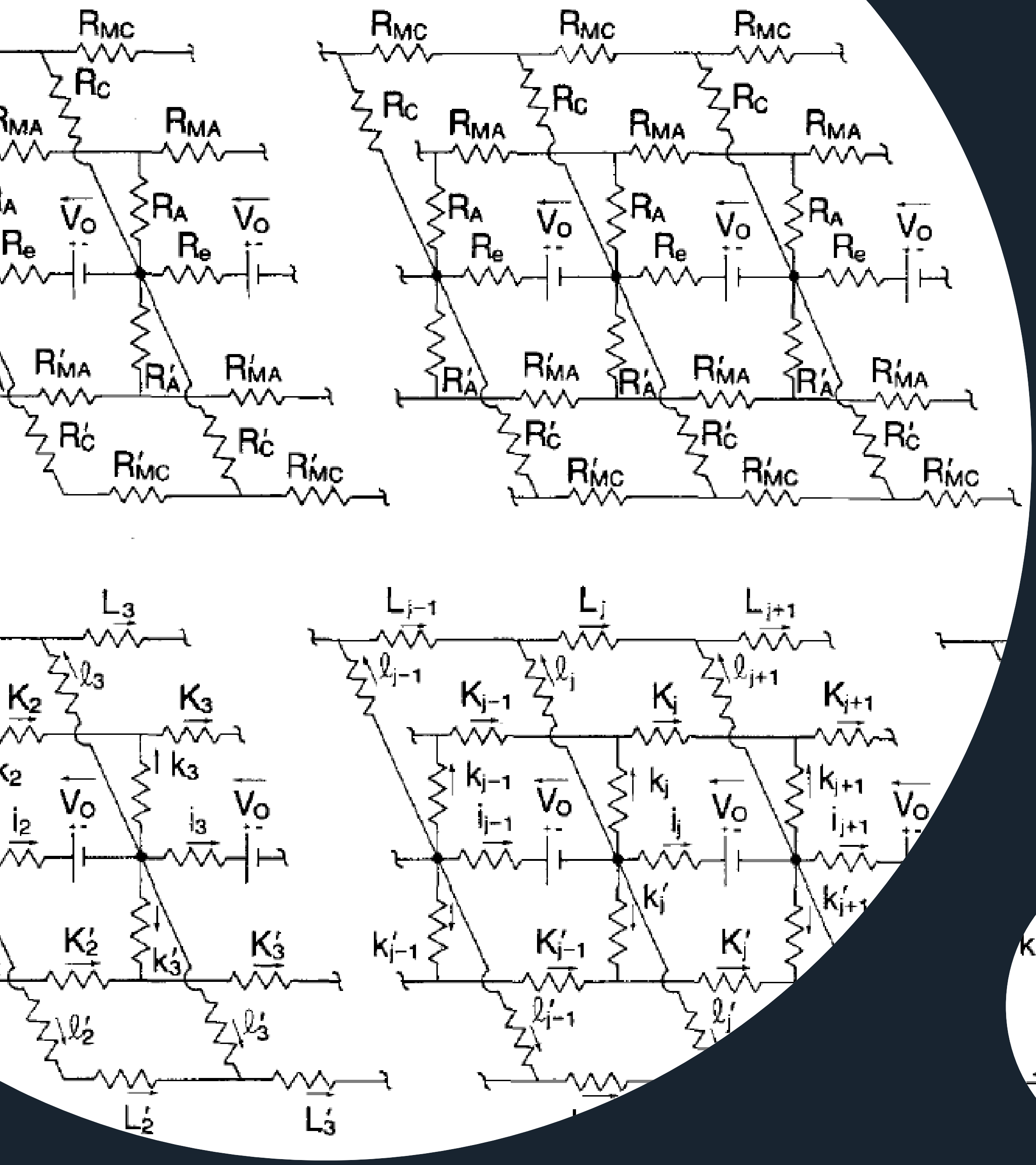
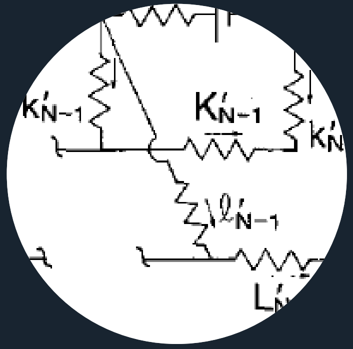
AWE in the past

- Designed to operate at a fixed and high load
  - Hydro-electric power the main power source
- Lesser focus on energy efficiency
  - Companies like Norsk Hydro produced electrolyzers, operated the plants and owned the power plants
  - Over the past 30-40 years water-electrolysis has been a niche application on the small-scale
- Historically low awareness around shunt-currents on AWE and its impact under dynamic and intermittent operation


Norsk Hydro plant Vemork, Norway, 1929-1988

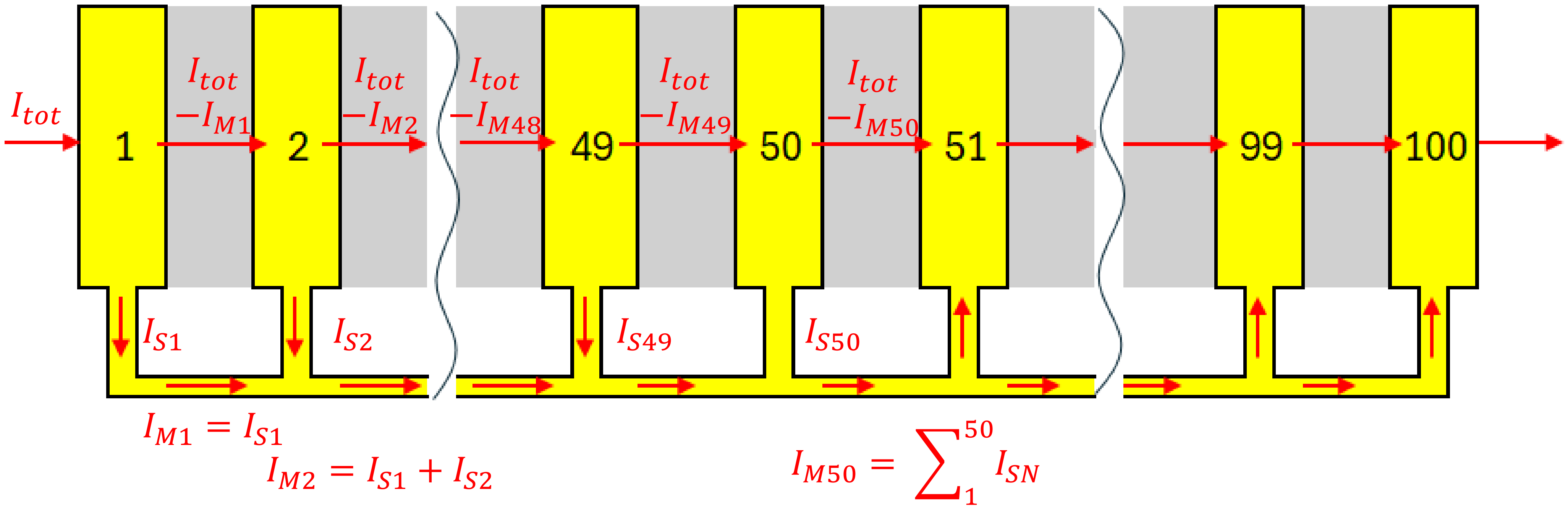




Shunt-currents (briefly) explained

Shunt-currents in a bipolar electrolyzer

- A portion of the current applied to the stack is being shunted via the common manifold system and bypassing the cells without contributing to production
- The magnitude of shunt-currents is given by the overall stack-polarization and the ohmic resistivity of the lye inside the manifolds



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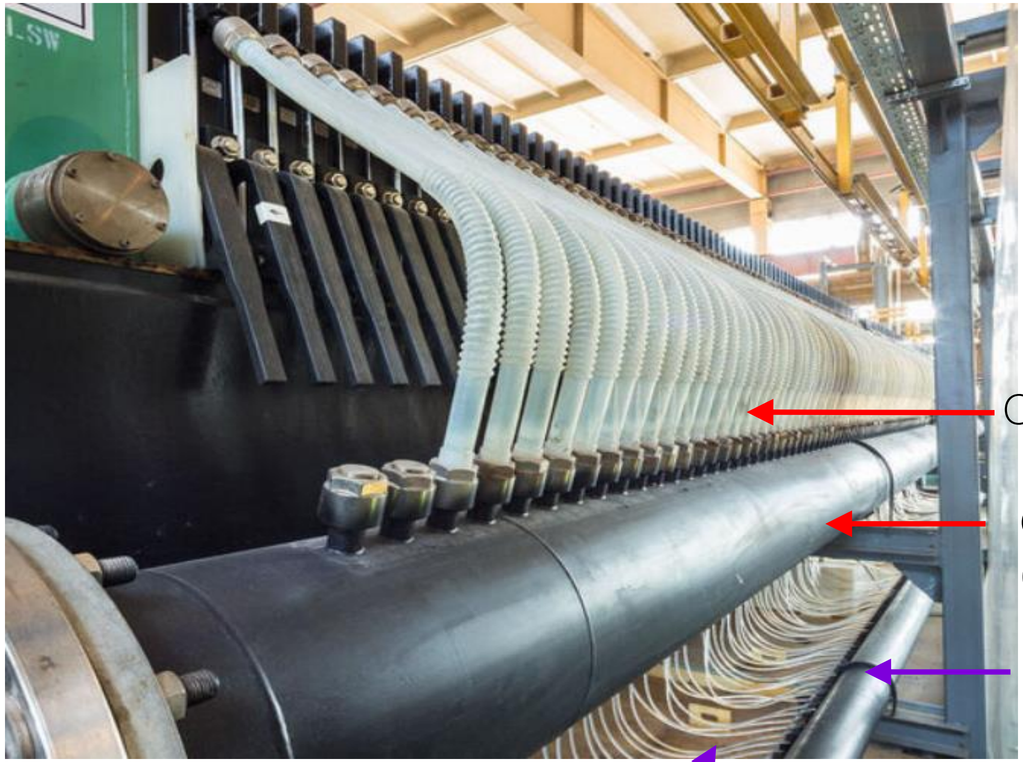
Different manifold design for different applications

Classic AWE with internal manifold system

Inlet/outlet port length ~ centimeter-size

Typical membrane-chlorine electrolyzer with external manifold system

Inlet/outlet port length ~ meter-size



Energy efficiency and shunt-currents under dynamic load

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Model to calculate shunt-currents

- Compare 100-cell and 200-cell stacks under variable load conditions
- A model to calculate shunt-currents is copied from Jupudi et.al. [1]
    - Takes into account the design and dimensions of the manifold system, gas fraction in outlet lye and cell voltage, all represented as electrical resistors in an analog circuit model
- Model parameters are chosen to represent more realistic values of large-scale stacks and are given in Table I
- Cell voltage given by a simple Tafel-equation with values in Table II
- Nominal load is assumed 10 kA

TABLE I. Parameter values.

Parameter	Value	Unit
Length inlet port	10	cm
Length outlet port	10	cm
Diameter inlet port	0,5	cm
Diameter outlet port	0,5	cm
Cross section area inlet port	0,2	cm^2
Cross section area outlet port (10 channels)	2,0	cm^2
Diameter inlet manifold	10	cm
Diameter outlet manifold	15	cm
Cell distance	5	m
Gas fraction	0,2	%
Conductivity lye	0,7	S/cm

$$U_{cell} = E0 + b*\log(I/I0) + I*Rs$$

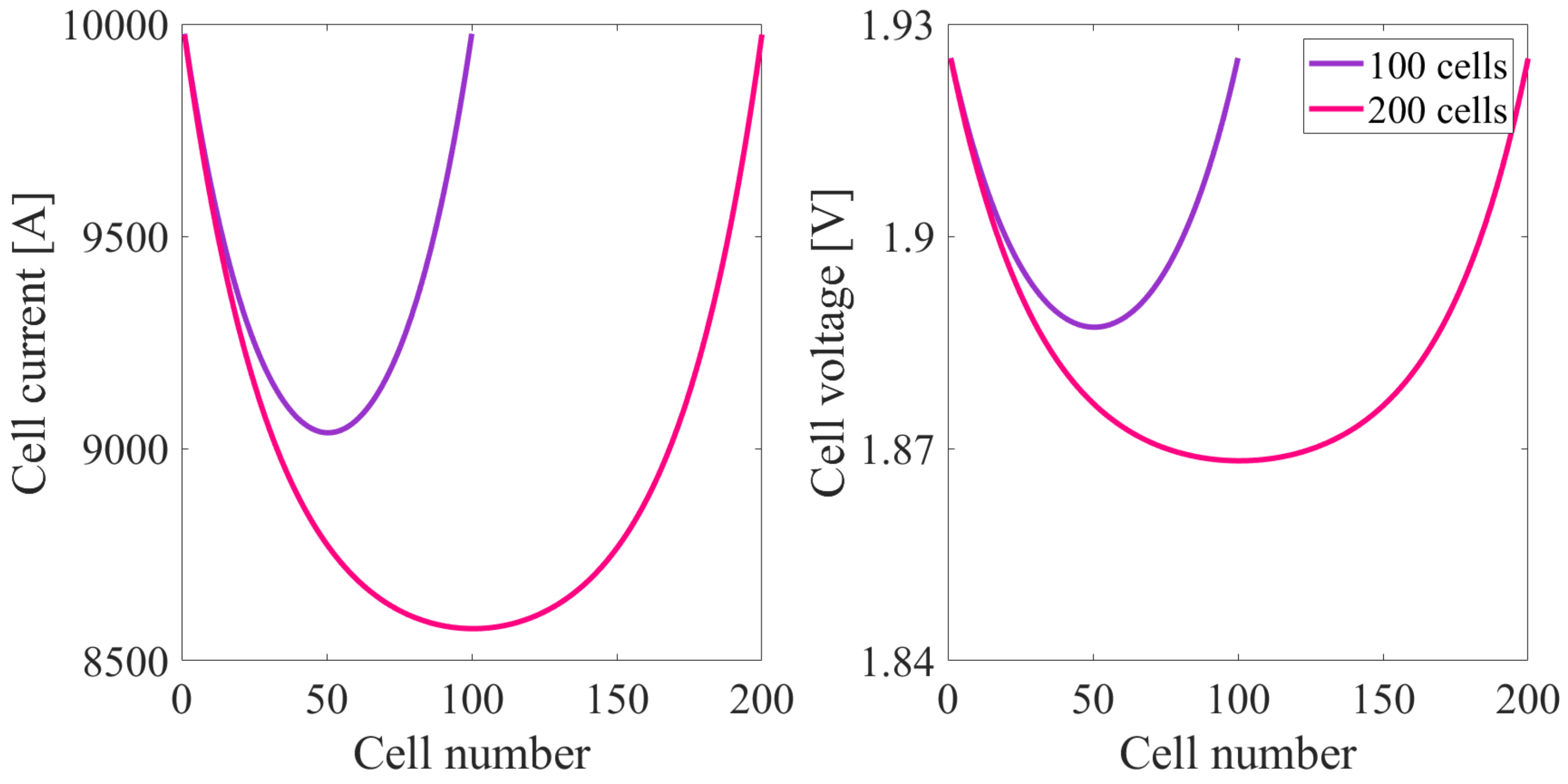
U_{cell}: cell voltage (V)
I: current (A)

TABLE II. Cell voltage calculation.

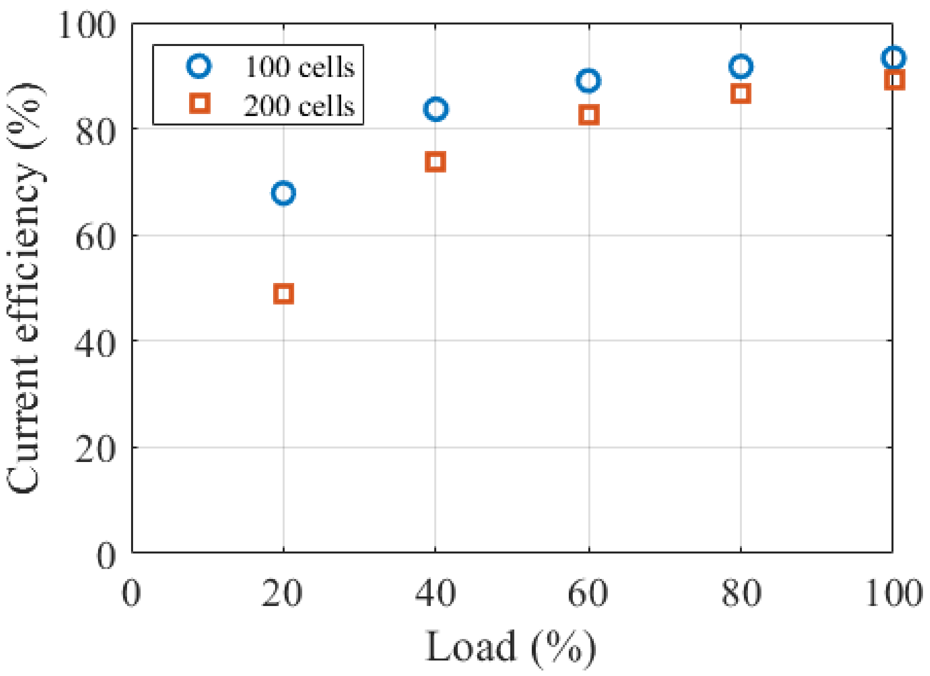
Parameter	Value	Unit
b	0.12	V/decade
E0	1.18	V
I0	5	A
Rs	3.5E-5	Ω

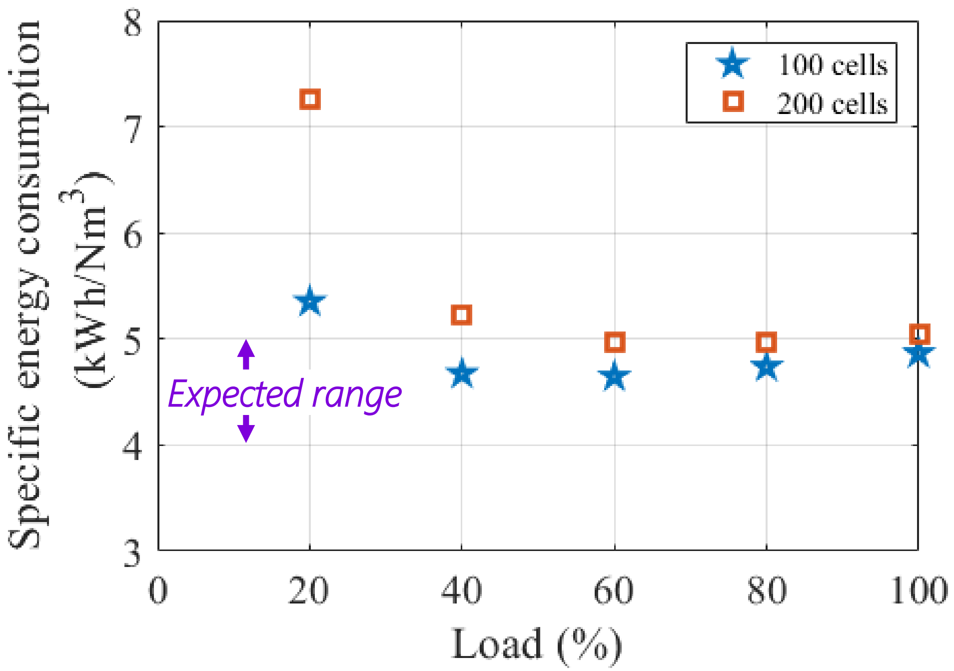
1. Jupudi, R.S., Zappi, G. & Bourgeois, R. Prediction of shunt currents in a bipolar electrolyzer stack by difference calculus. J Appl Electrochem 37, 921–931 (2007)

Cell current and cell voltage dynamics over the stack-length



Current efficiency and energy consumption vs. load and number of cells

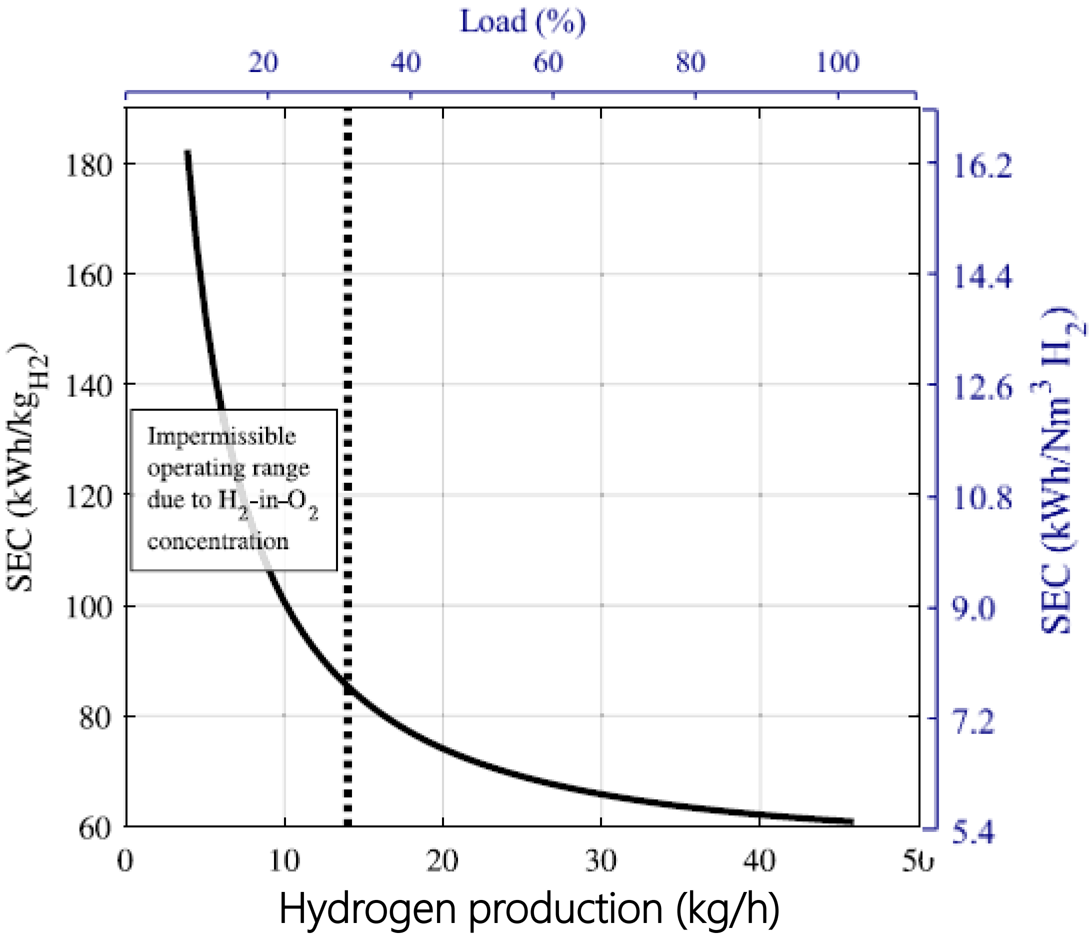




Large-scale high-pressure AWE electrolyzers with simple and internal manifold (2016)

- 3 MW high-pressure AWE-plant in Finland
  - Pressure: 16 bar
  - Stack: 2x163 cells
- SEC dramatically increases towards lower load due to loss in current efficiency
- Low-load limit increases due to bad gas-purity
- Not favorable under dynamic loads and operation with renewable energy
- Plant delivered by HydrogenPro and Chinese based Tianjin Hydrogen Mainland Equipment in 2016

Load	50%	100%
Current efficiency	60	85
SEC (kWh/Nm^3)	6.3	5.5



Source: G. Sakas, A. I-Rioja, S. Pöyhönen, A. Kosonen, V. Ruuskanen, P. Kauranen, J. Ahola, "Influence of shunt currents in industrial-scale alkaline water electrolyzer plants", *Renewable Energy*, Volume 225, May 2024, 120266

Relevant references

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Electrode degradation and shunt-currents under intermittent operation

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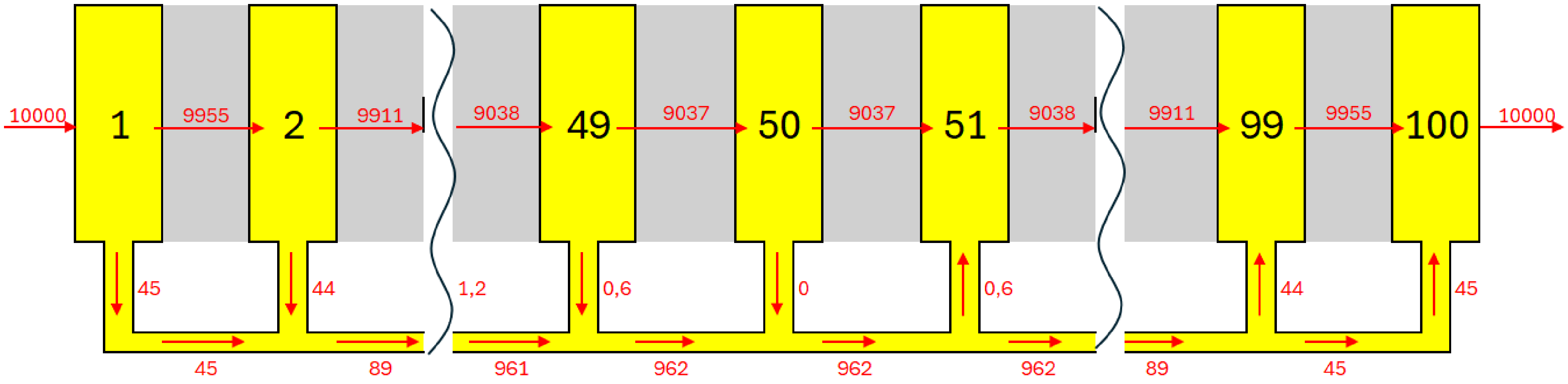
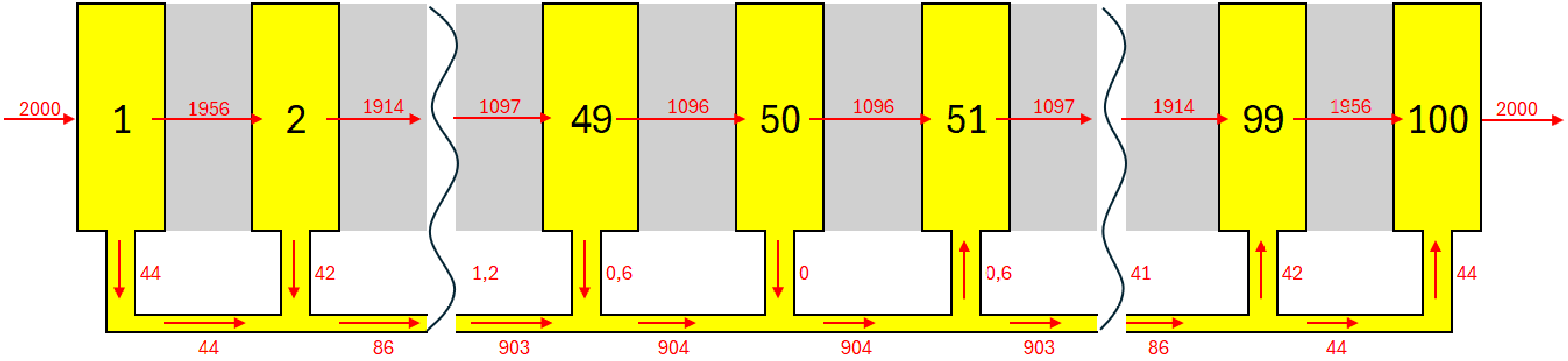
At full load



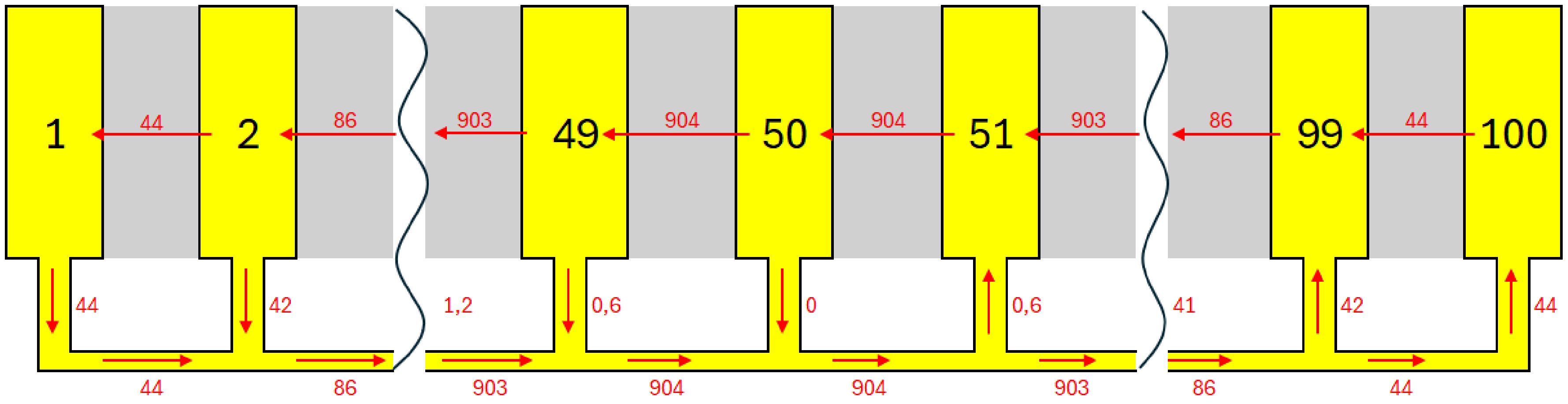
At low load



Discharge under shutdown

- The overall polarity over the cell stack, and the migration field over the manifold system, is driving the shunt-currents
  - Independent on current direction inside the cells
- Under discharge the reverse current inside the cells must balance the shunt-currents over the manifold system leading to a much higher discharge current from the center of the stack and lower towards the endplates
- Stack polarization and shunt-currents will immediately start to decrease

At shut-down



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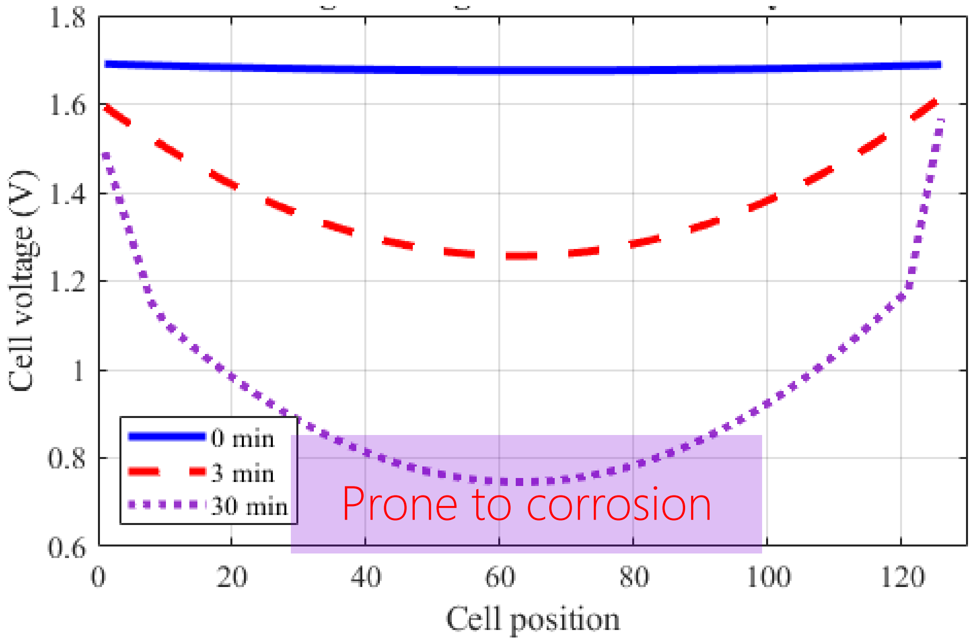
Discharge of large membrane chlorine-electrolyzer stack

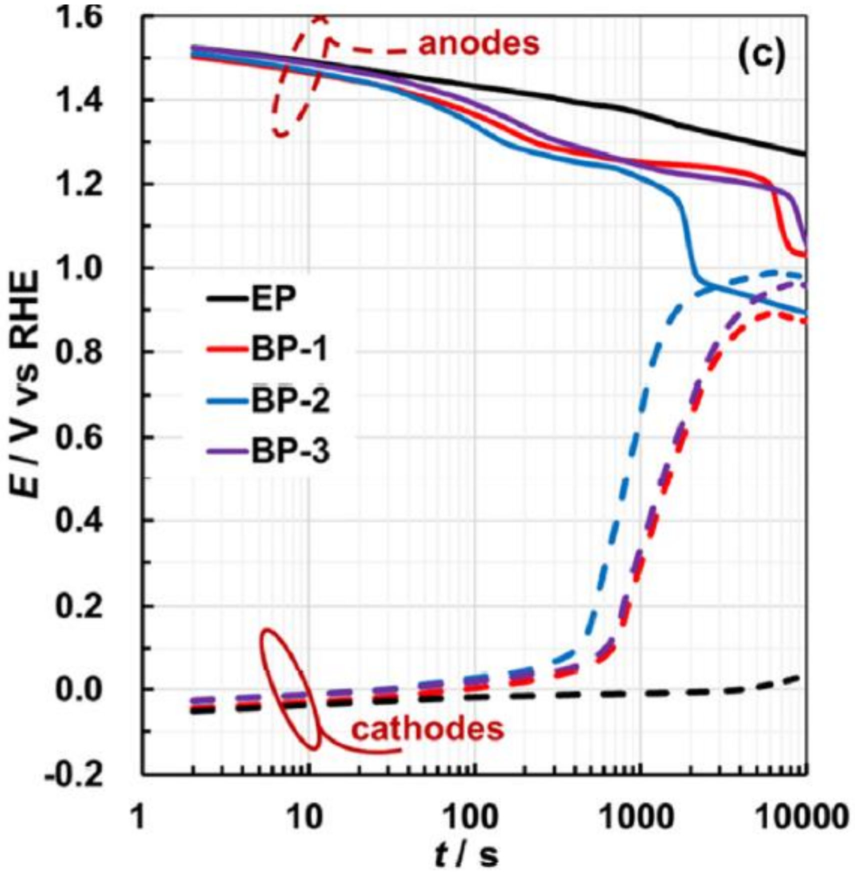
- Typical discharge behavior of a membrane-chlorine electrolyzer (126 cells)
  - Using Voltage Monitoring System to measure cell voltages
- Discharge is always faster towards the center position
- Electrodes in membrane-chlorine electrolyzers are often prone to corrosion in the center-cells
- All bipolar electrolyzers with a common manifold system will show the same U-shape behavior in current and cell voltage
- Corrosion depends on the discharge potential of oxygen and hydrogen electrode



Effects of operation and shutdown parameters and electrode materials on the reverse current phenomenon in alkaline water analyzers

Ashraf Abdel Haleem [a,*], Jinlei Huyan [b], Kensaku Nagasawa [a], Yoshiyuki Kuroda [c], Yoshinori Nishiki [d], Akihiro Kato [d], Takaaki Nakai [d], Takuto Araki [b], Shigenori Mitsushima [a,c]

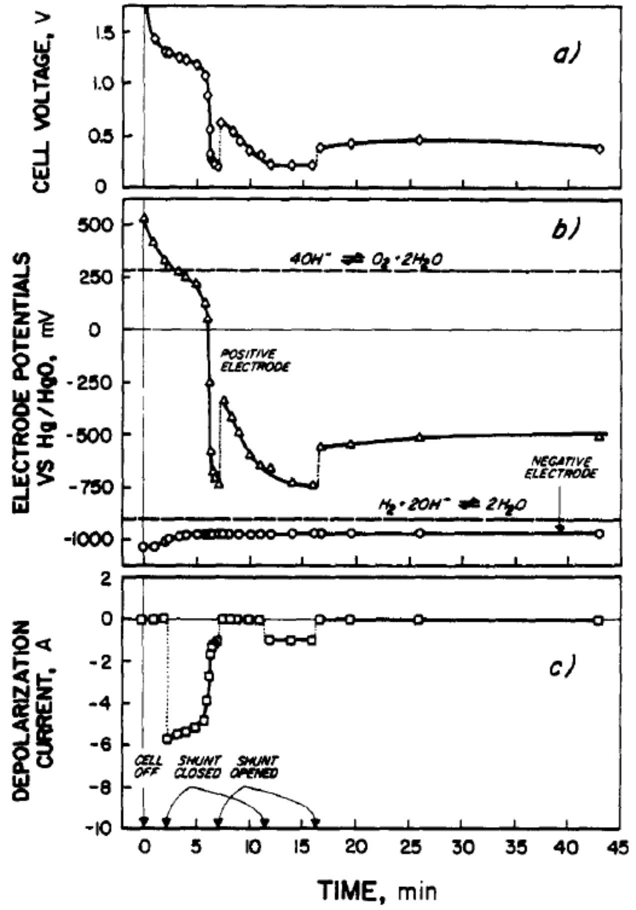
Journal of Power Sources 535 (2022) 231454



ELECTROCATALYST PERFORMANCE IN INDUSTRIAL WATER ELECTROLYSERS

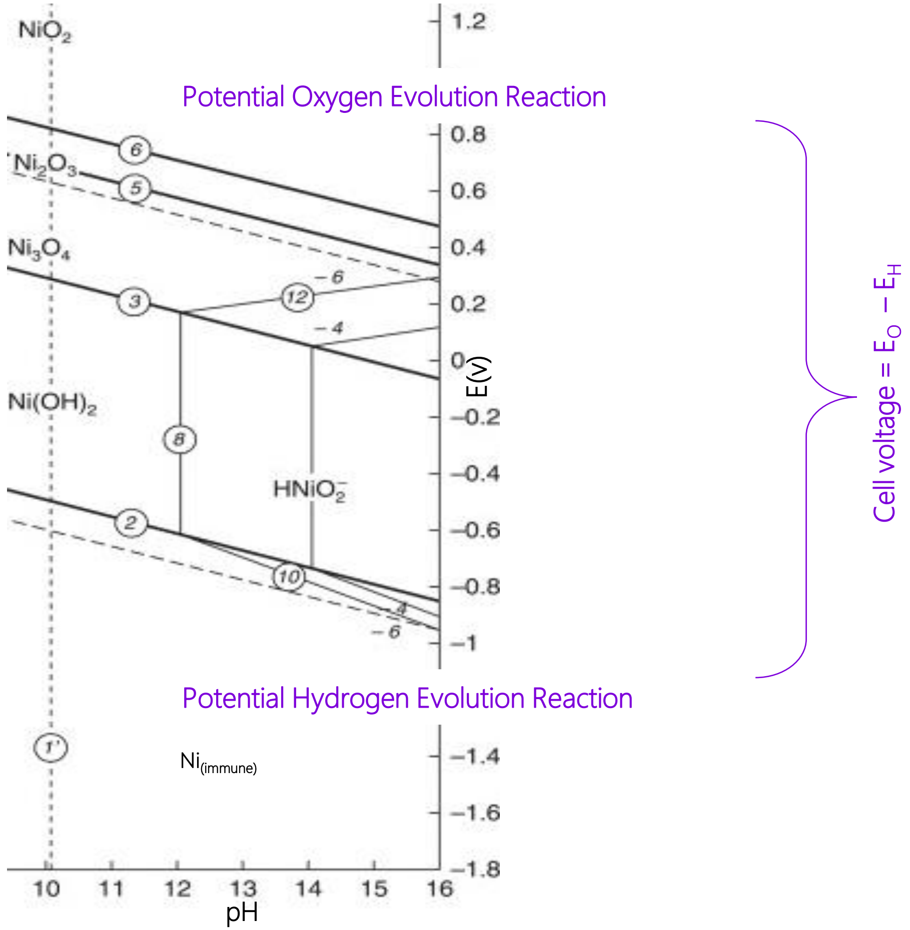
M. B. I. Janjua and R. L. Le Roy

Int. J. Hydrogen Energy, Vol. 10, No. 1, pp. 11–19, 1985.



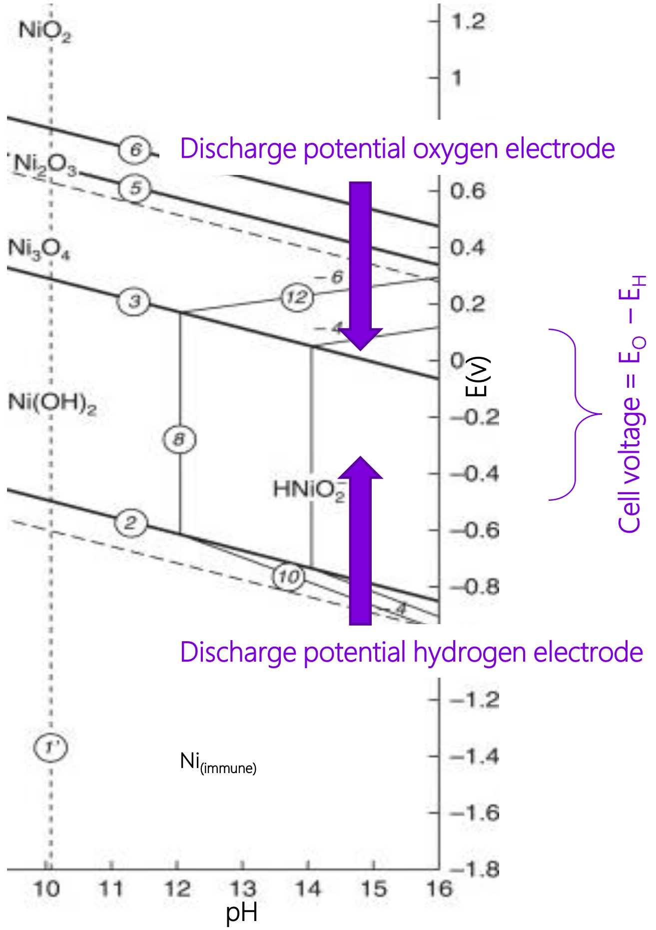
Pourbaix diagram showing the thermodynamically stable phases on nickel

- Material stability under shutdown can be understood from the Pourbaix diagram
- At low potentials nickel is in immune state
- At high anodic potentials nickel forms stable oxides
- Cell voltage will be the difference in potential of oxygen and hydrogen electrode



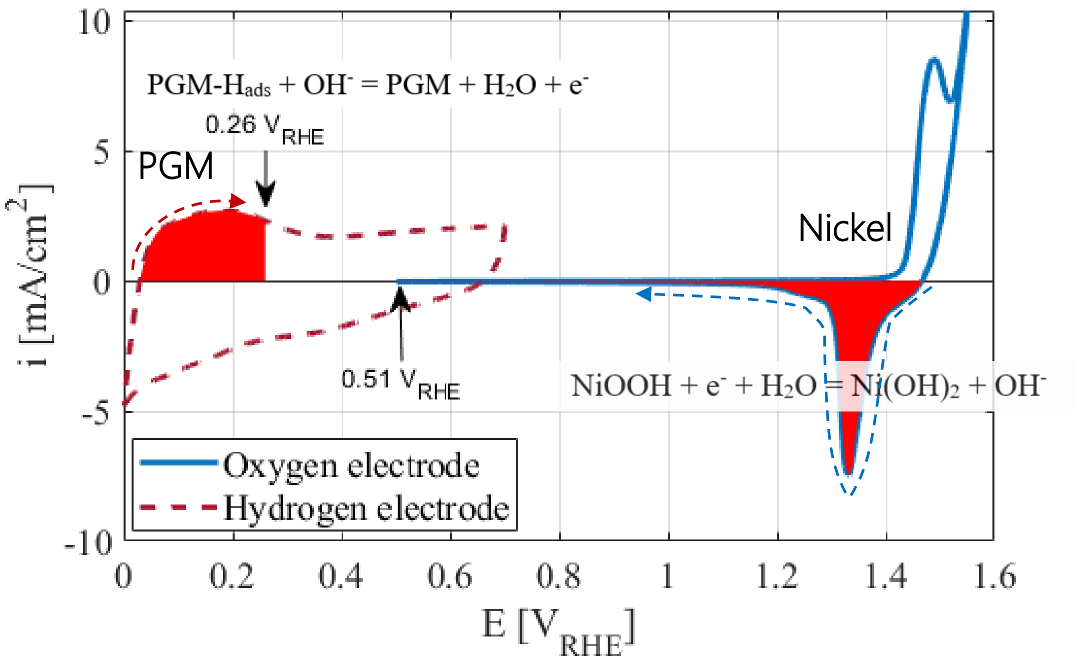
Pourbaix diagram showing the thermodynamically stable phases on nickel

- During shutdown and discharge the potential of oxygen and hydrogen electrode will move into the non-stable region ($HNiO_2^-$) being prone to corrosion
- Corrosion on one or the other electrode depends on to how much each respective electrode is being polarized



Discharge potentials must be understood

- How much the two electrodes are discharged depends on
  - Capacitance, discharge kinetics, shunt-currents and their position in stack
- Discharge behavior can to some extent be determined from their respective cyclic voltammograms
  - Hydrogen Electrode: Platinum Group Metal (PGM)
  - Oxygen Electrode: Nickel
- Discharge currents will follow the dotted arrows on each electrode
  - The discharge current on the two electrodes must at all time be equal
- Once the potential of the oxygen electrode has passed over the nickel-redox peak at 1.3 V, the oxygen electrode will have to discharge much faster/further to accommodate the discharging current of the hydrogen electrode
  - Potential on the nickel electrode may quickly move down to HER potentials
- At cell voltage = 0.25 V; oxygen electrode polarized by 1 V, hydrogen electrode only polarized by 0.26 V
  - Nickel electrode may go down to potential for hydrogen evolution
- Hydrogen and oxygen electrodes must be matched with respect to their discharge properties and material stability to avoid extreme polarization of either electrodes
- One way to come around the stability issue under shutdown is to enable current protection
  - Requires minimal shunt-currents



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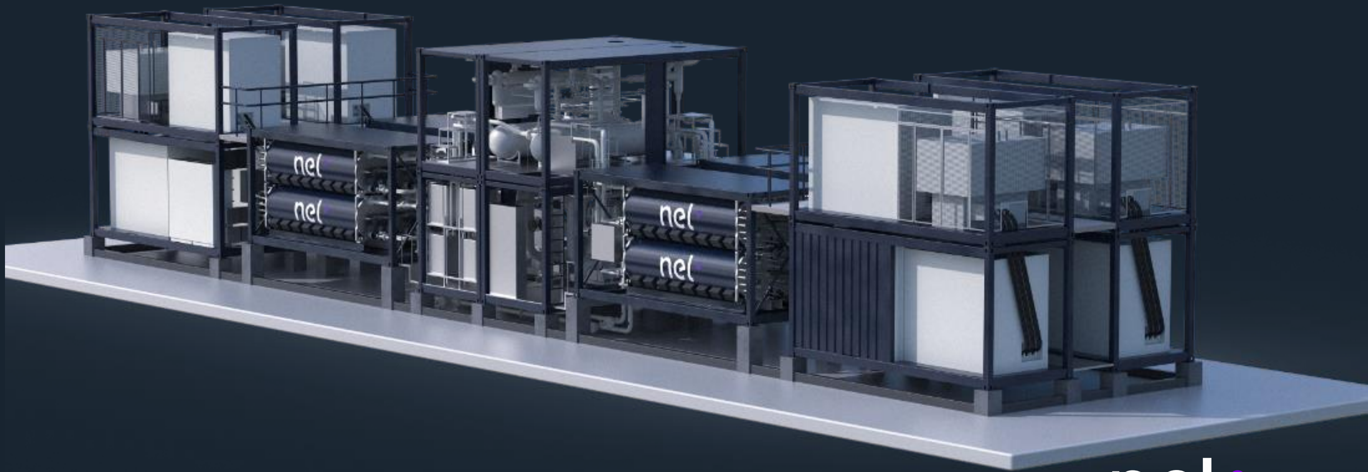
Summary

- High-pressure large AWE-stacks with conventional internal manifold system may have serious challenges with shunt currents in combination with renewable energy operation
  - Low CE and high SEC
  - Increased electrode corrosion and shorter lifetime of stack
- Improved manifold design is required to enable high-pressure AWE and large stacks in combination with renewable energy system

AWE technology by Nel - now and future

- Atmospheric AWE
  - Shunt-currents blocked by large gas fraction and current efficiency relatively high over the load range
  - Nickel based electrodes
    - Resilient towards corrosion during shutdown
    - Low current density and atmospheric pressure => large footprint
- Next generation high-pressure AWE
  - Internal, but *advanced* manifold system to mitigate shunt-currents
  - High energy efficiency over the entire load range
  - Enabling current-protection during shutdown
    - Use of advanced non-PGM electrodes
  - VMS-ready
    - Better surveillance for increased safety, preventive maintenance and process optimization



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