Video recording link: https://mailchi.mp/energystorageforum/sbcvideorecordings4

Ammonia For Cost-Effective Storage And Distribution Of Large Quantities Of Renewable Energy

Dr Camel Makhloufi

ENGIE Lab CRIGEN

E-Fuel Key Program co-manager & Power-2-X R&D Program Leader

19th May 2021

14th Energy Storage World Forum

RESTRICTED | INTERNAL | SECRET

ENGIE × Green Hydrogen

167,000
employees

€60.6 billion
in revenue

250 000 km
of distribution grid worldwide

37 000 km
of transport grid worldwide

58 GW
of natural gas capacity

25 GW
of renewable capacity

105 GW
of installed power capacity

Large scale industrial projects

- Ammonia
- Methanol
- Refineries
- Mining

Decentralized projects

- Light and heavy-duty mobility

Pilot projects/ new usages

- H_2 injection
- Trains
- Mining trucks
- Power production

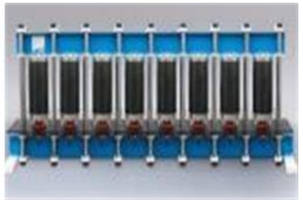
PpP Pau Porte des Pyrénées Ville de Pau · HYNOVAR · SMT Syndicat Mixte des Transports Artois-Gohelle · MÉTHYCENTRE · HY PORT · GRHYD · EffiH2 by ENGIE · Jupiter 1000

ENGIE 2030 target	4GW of Hydrogen production capacity 700 km of H2 pipeline & 1 TWh storage capacity 100 refueling stations

Hydrogen Lab @ ENGIE Lab CRIGEN
Working all along the value chain

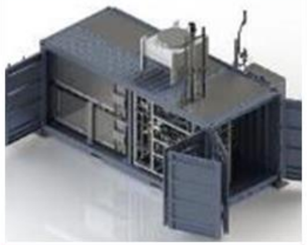
- Production
- Storage & Transport
- Usage

NEPTUNE (FCHJU)



REFLEX (FCHJU)

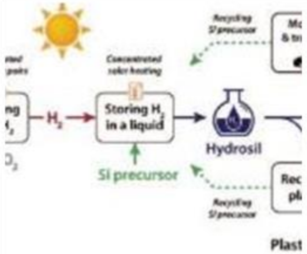
MULTIPLHY (FCHJU)



MACBETH (SPIRE)

HYCARE (FCHJU)

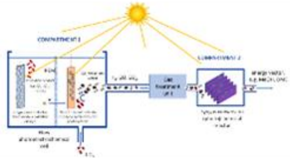
SUN-TO-X (H2020)



ARENHA (H2020)

C2FUEL (H2020)

CONDOR (H2020)



WINNER (FCHJU)

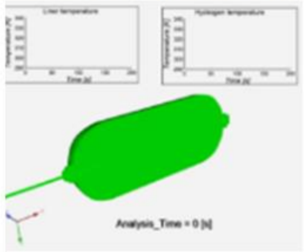
GRHYD (ADEME)

HYCAUNAIS (ADEME)

LIVING H2 (ANR FR-ALL)

METROHYVE (EMPIR)

PRHYDE (FCHJU)

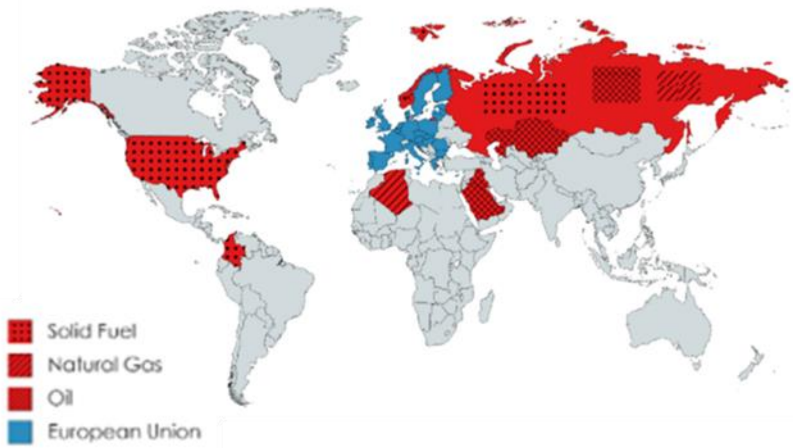


MULTHYFUEL (FCHJU)

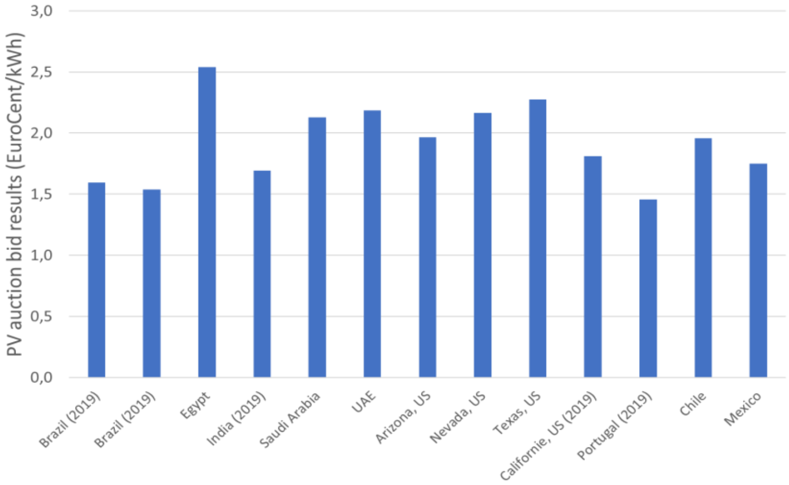
Electrofuels allows new energy corridors and energy supply diversification

Hydrogen and electrofuels are key for new energy corridors and energy supply diversification through international trading

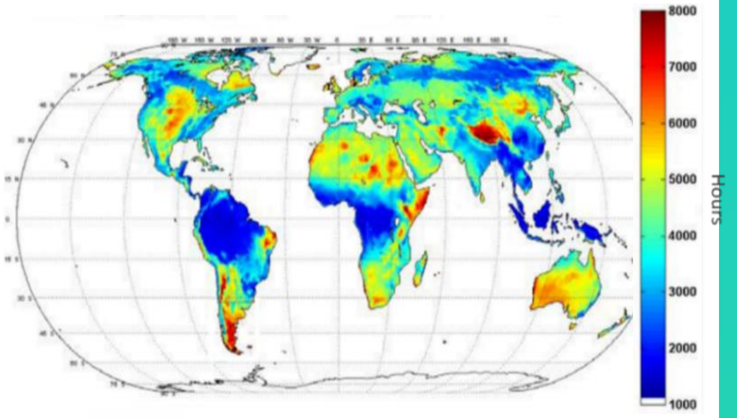
- Main fossil fuel exporters to Europe



- Lowest PV auction bid worldwide in 2018 and 2019



- Hybrid Wind and PV cumulative full load hours – Source VTT

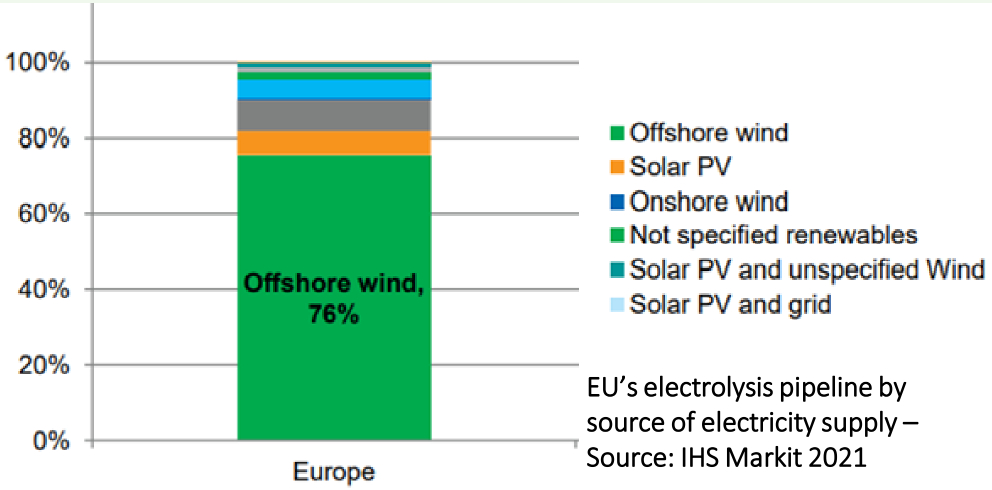


New energy corridor with countries showing electricity economic potential lower than 30€/MWh with cumulative load hours higher than 5000 hours are possible!

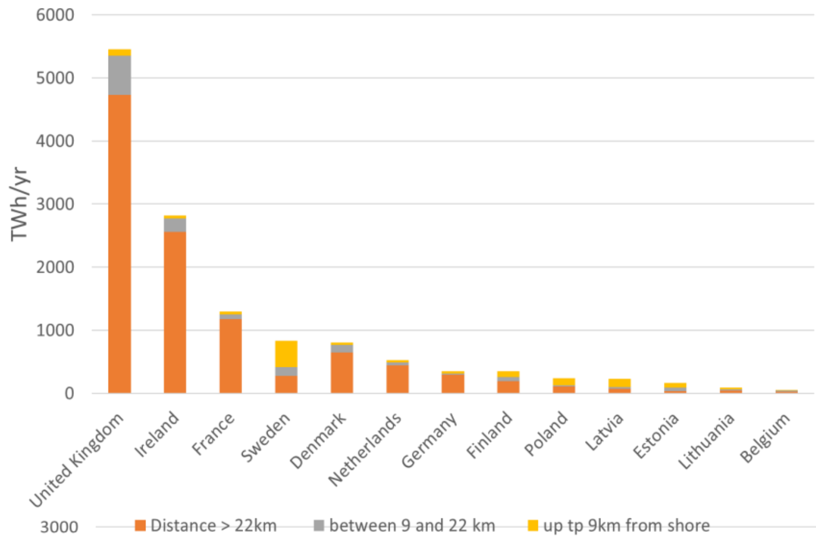
In a longer term vision, Electrofuels may promote far offshore wind energy

Key Insights

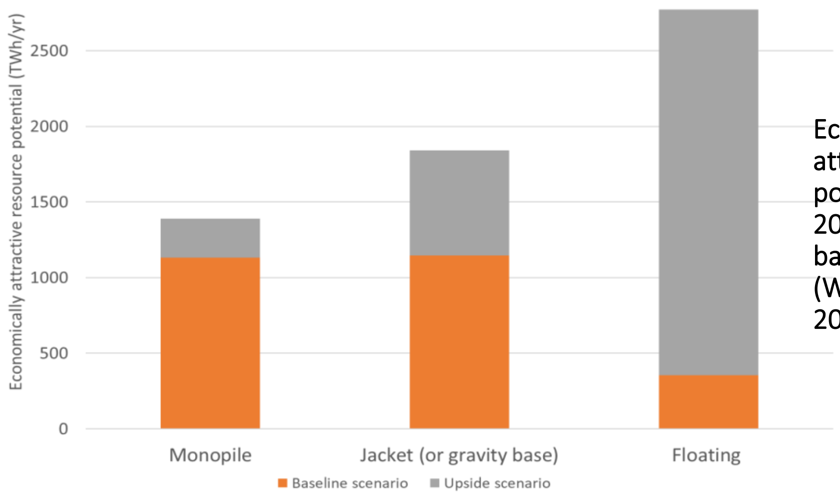
- Estimated European potential of offshore wind resource ranges between 600 and 1,350 GW for a cost of 50 to 65€/MWh.
- **78% of electrons planned for green hydrogen comes from offshore wind!**
- By 2030, the potential of offshore wind could possibly represent between 80% and 180% of the EU's total electricity demand.
- Higher technical potential is located at >20 km, this creates high associated transmission over-costs if undersea cables are used.



EU's electrolysis pipeline by source of electricity supply – Source: IHS Markit 2021

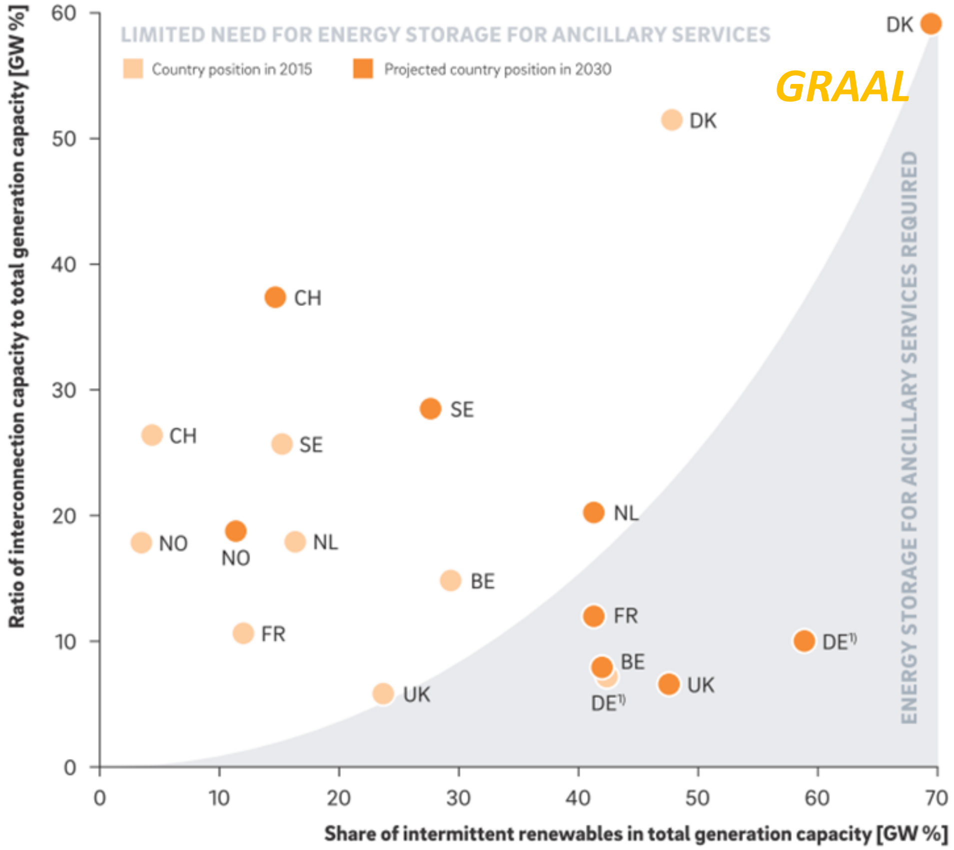


Technical resource potential at the end of 2030 by country (2017)

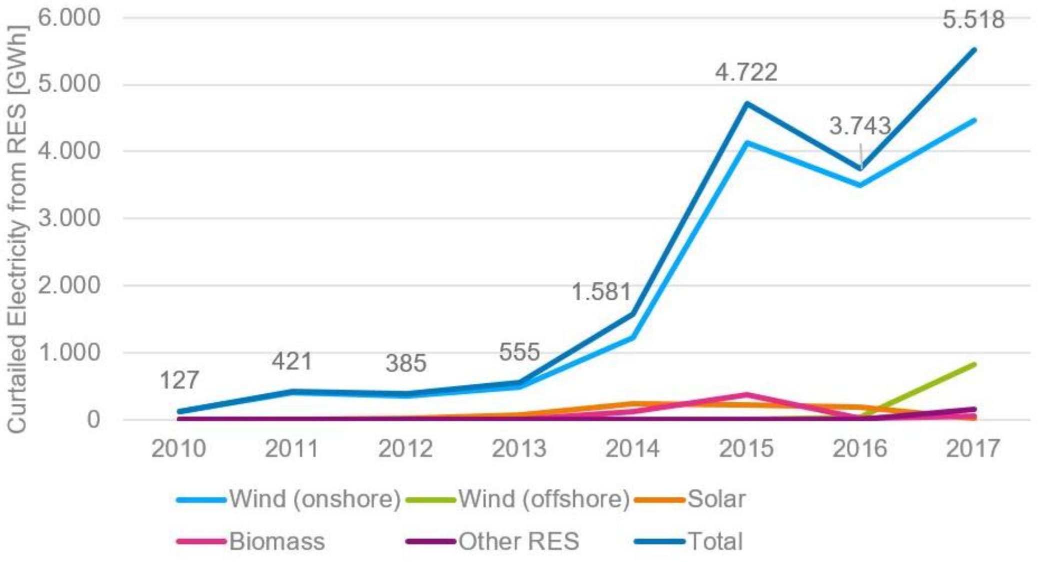


Economically attractive potential in 2030 by sea basin (WindEurope)-2017

Electrofuels will support RE penetration through long term storage and dispatch, reducing curtailment



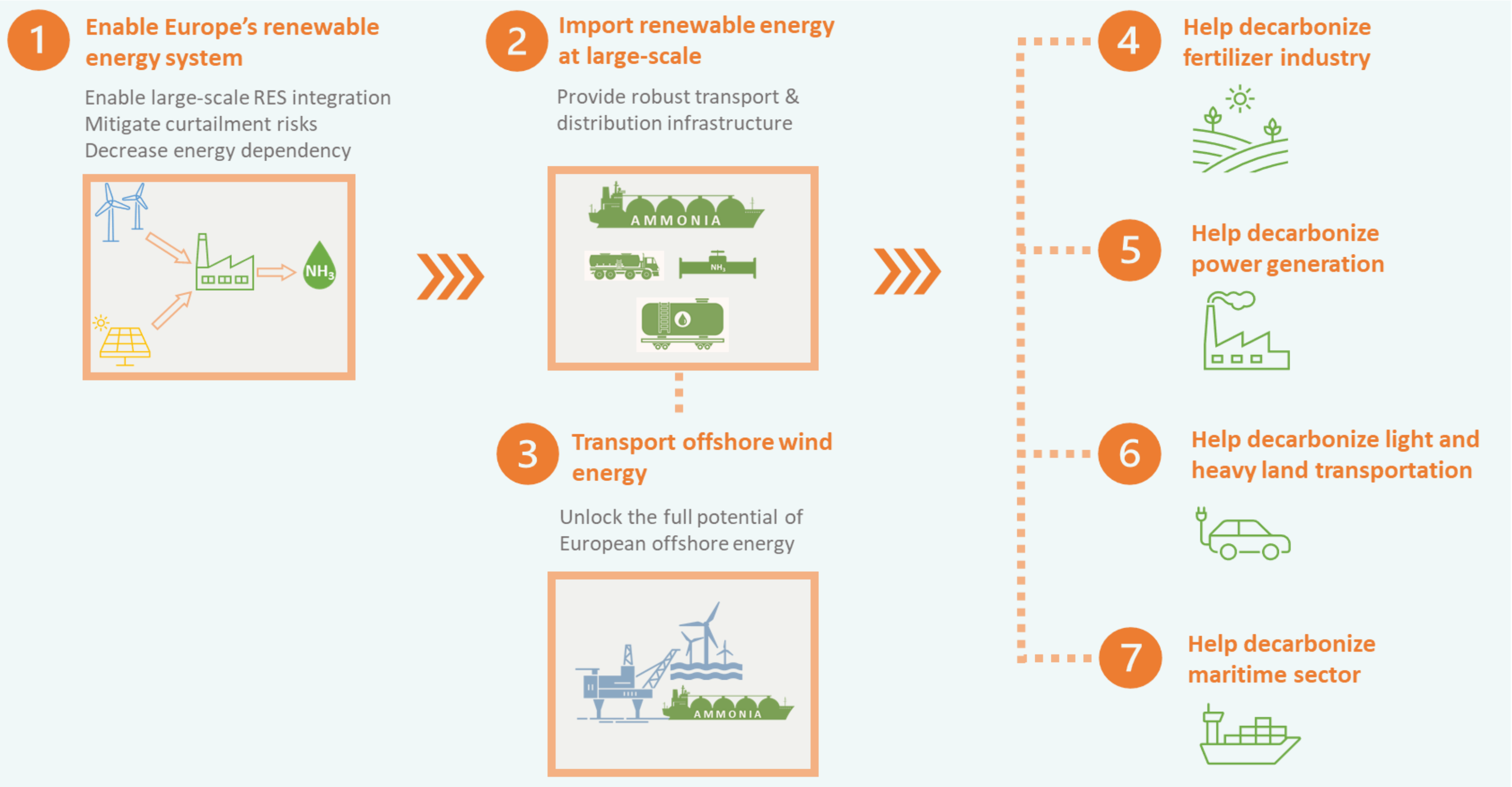
Need for energy storage in provision of ancillary services – Source: ENTSO-E, Roland Berger 2017

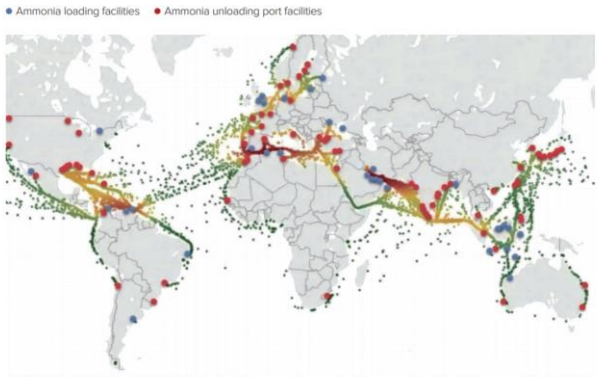


Curtailed renewable electricity in Germany – Source: Tractebel ENGIE 2018

EU countries with large shares of intermittent renewables and low interconnection capacity will heavily rely on the adoption of energy storage solutions.
For instance, Germany relies on 40 GWh of pumped-storage power as the only seasonal storage solution. So far, the government was compensating RES plants for curtailed energy. Compensation payments amounted to 478M€ in 2017 alone.

A possible role of ammonia in the future European green energy system

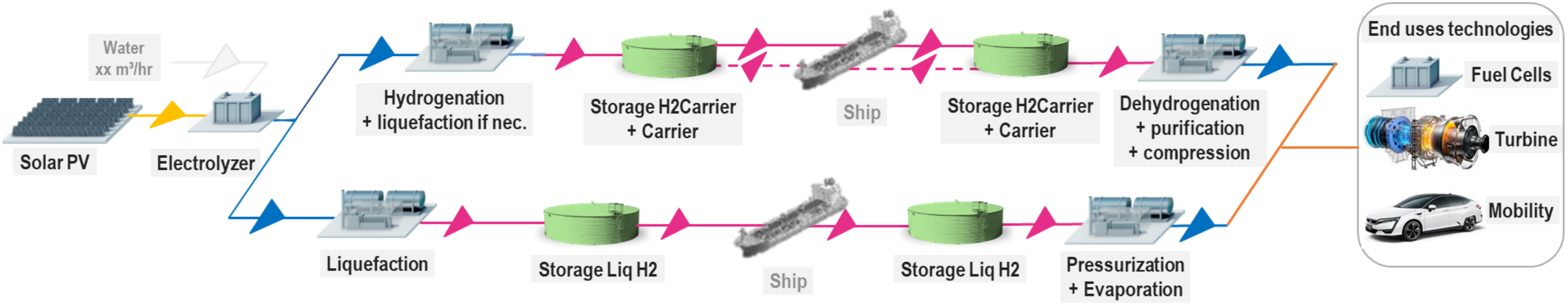




Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers and existing ammonia port facilities – Source: The Royal Society, 2020

Long distance hydrogen transportation : case study in Morocco

- Four different hydrogen carriers are considered (Liquid hydrogen, LOHC, NH_3, e-methane) : hydrogenated, transported and dehydrogenated except for SNG
- Electricity is produced from PV or from hybrid PV and wind electrical sourcing in three different city in Morocco : Essaouira, Agadir and Tarfaya
- Discharged energy cost are calculated for 3 time frame : 2030,2040 and 2050 respectively for 5, 10 and 20 TWh equivalent

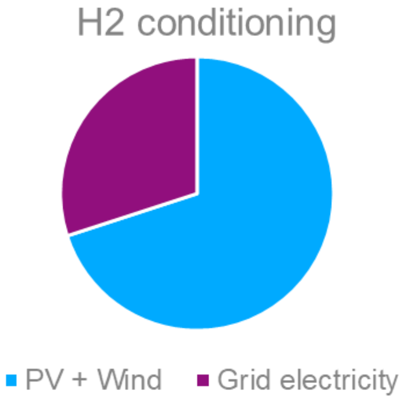


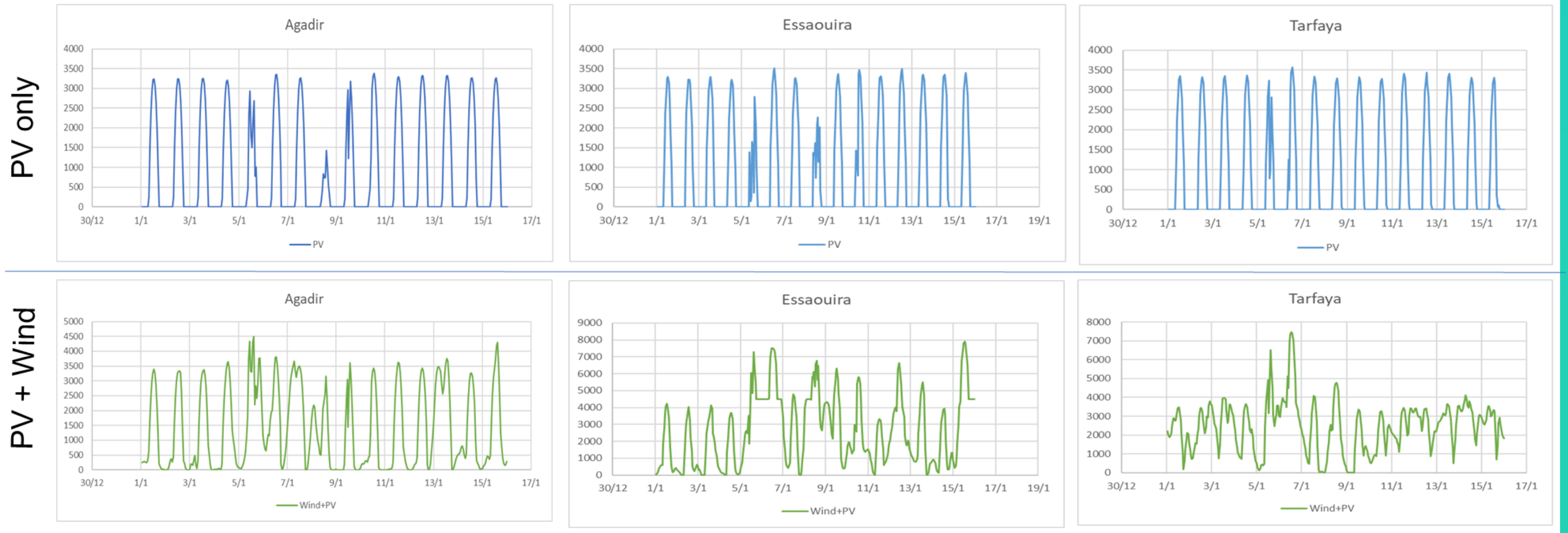
Electricity cost and profile in Morocco

	2030	2040	2050
PV	42 €/MWh	32 €/MWh	23 €/MWh
Wind	42 €/MWh	34/MWh	29/MWh
Grid	>100 €/MWh	>100 €/MWh	>100 €/MWh
ELY	450€/kW	300€/kW	300€/kW

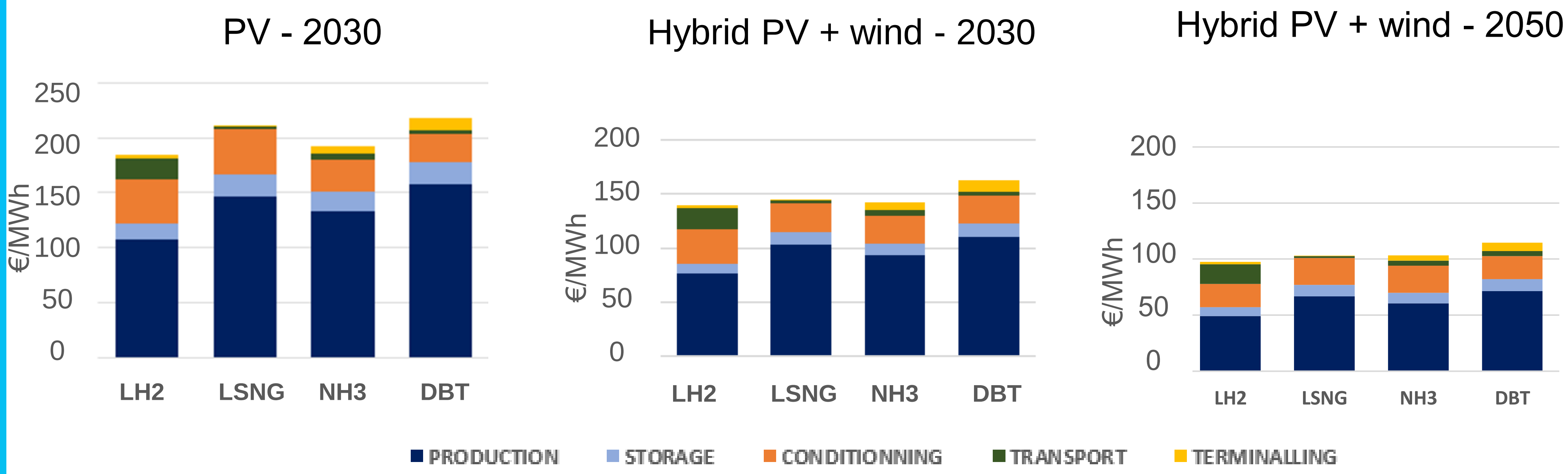
Sources :

- PV : "Current and Future cost of photovoltaics" Fraunhofer ISE
- Eolien : 2009 NREL "Wind LCOE" for IEA, "Forecasting wind energy cost ans cost drivers" IEA Wind + USDoE June 2016
- Grid : Enerdata, internal estimate





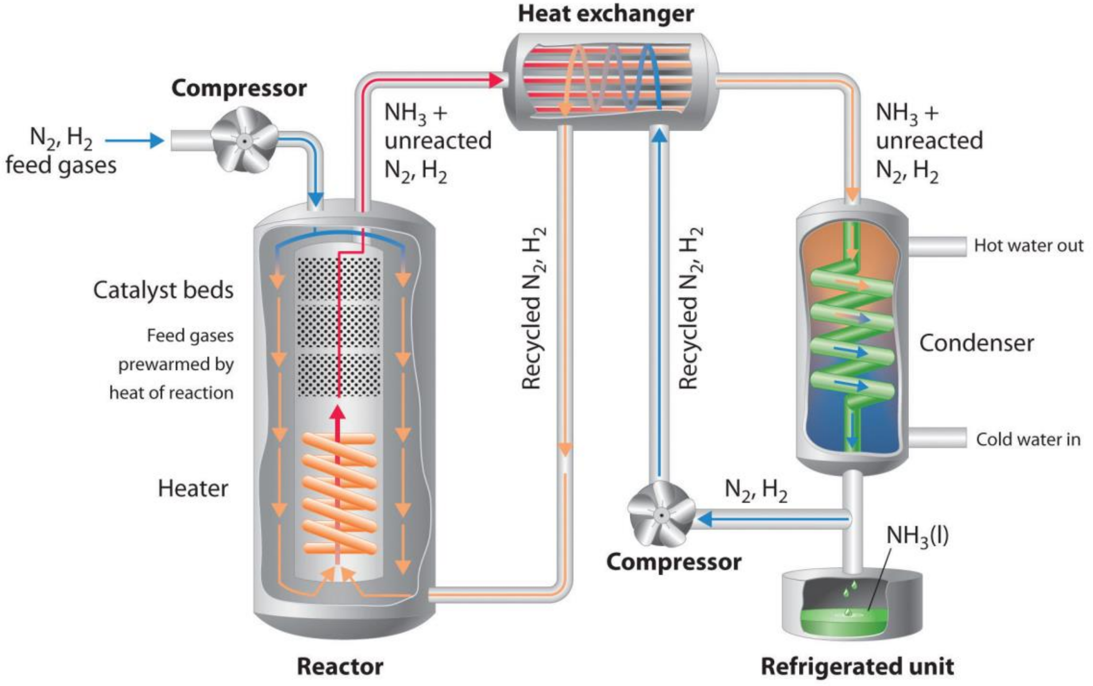
Electrofuels production cost – Various solutions and no clear winner



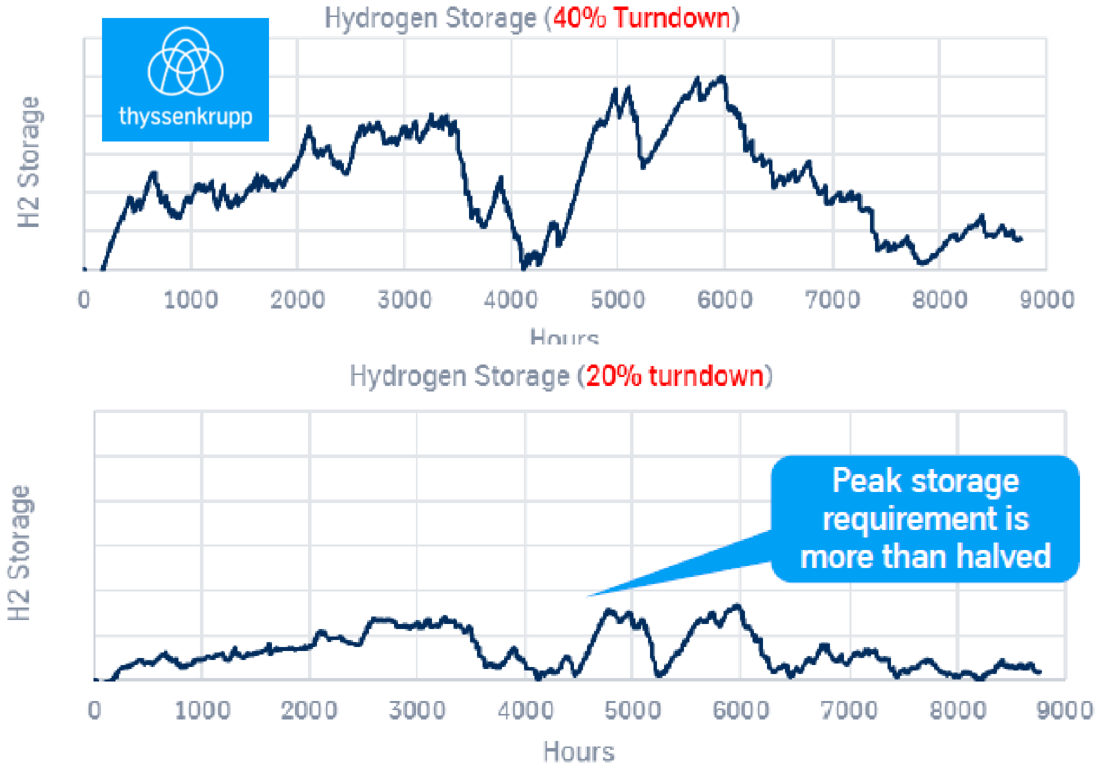
Y. Ishimoto and al. 2015.
D. Teichmann and al., 2012.
M. Eypasch et al.,2017.
M. Reuß, 2017.
M. Appl, 2012

- H_2 production cost is predominant with strong effect of hybridation on levelized cost of discharge energy
- Apparently, LH_2 and NH_3 are the most promising. Results must be considered with caution since maturity levels of these various solutions are very different
- While hybridation allows high renewable load factor improving economics; **E-Fuel synthesis loop flexibility and cracking technologies remain to be studied and improved.**

Green ammonia competitivity suffers from lower flexibility of converters and compressors

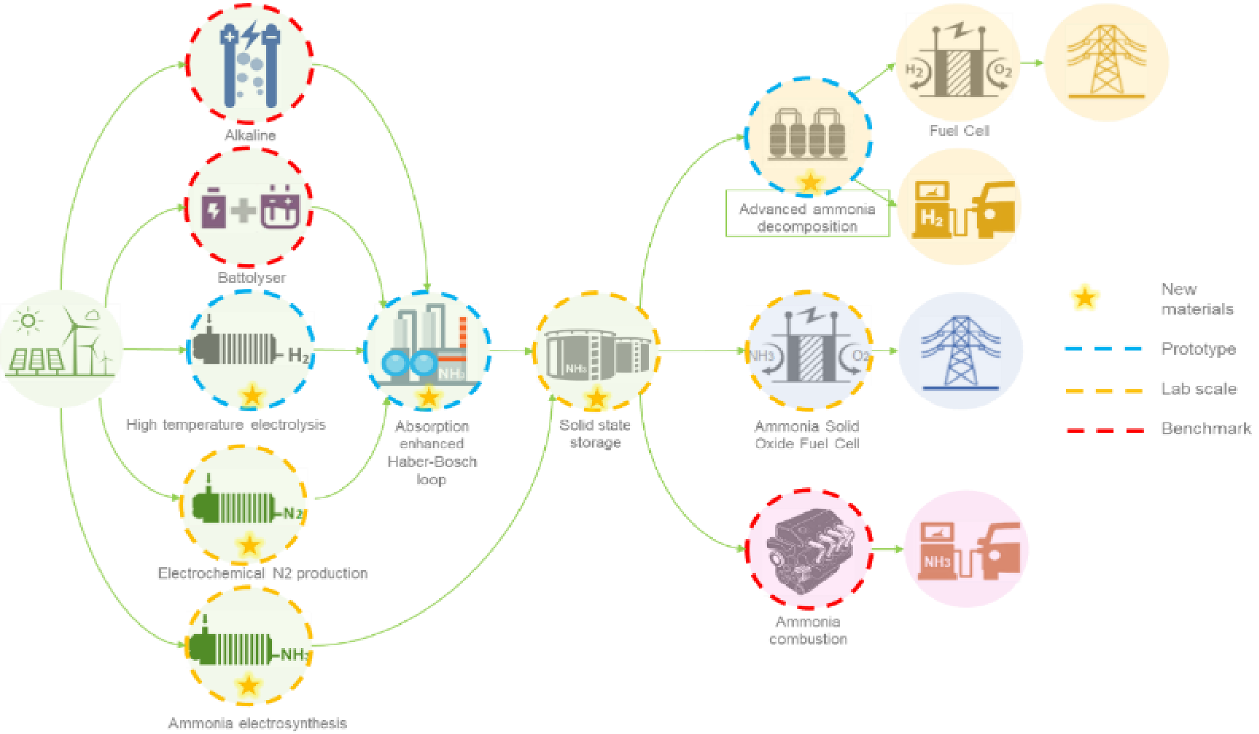


Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. Collin Smith, Alfred K. Hil and Laura Torrente-Murciano 28th December 2019



From Micro to Mega How the green ammonia concept adapts
Ammonia = Hydrogen 2.0 Conference | Aug 2019 | Rhys Tucker and Karan Bagga
thyssenkrupp Industrial Solutions

ARENHA : from power to ammonia to energy discharge
Flexible ammonia synthesis at lower pressure



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862482.

Ammonia cracking technologies are needed to unleash the full potential of ammonia as energy vector

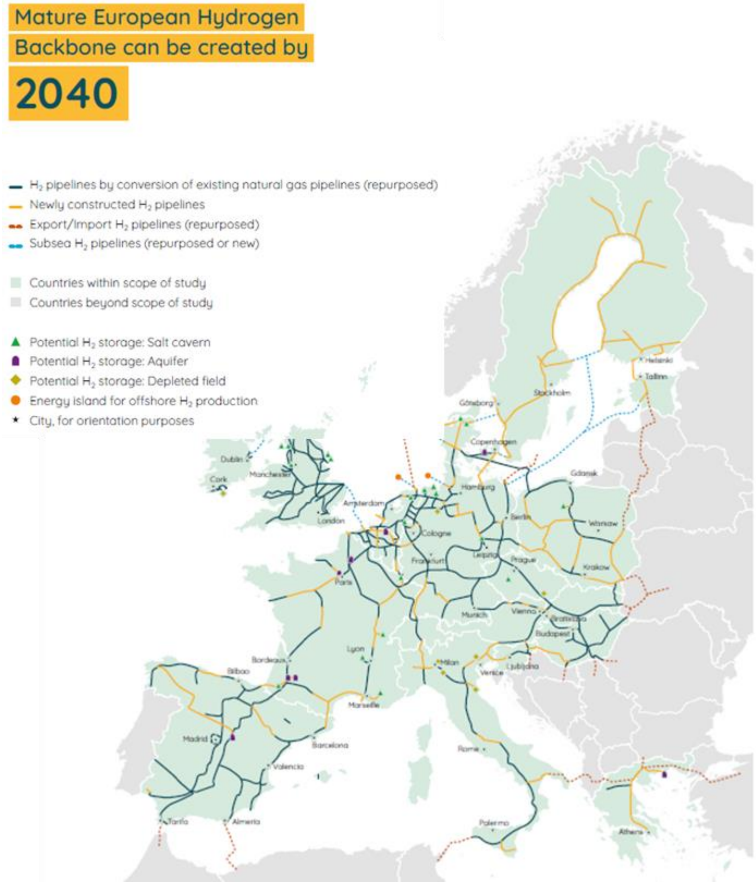
Decentralized cracking : onsite or on board

Hydrogen refuelling station

Fuel cell and turbine for power generation (Genset data centers, shipping, power plants)

On board generation for Internal combustion engine (truck, ships)

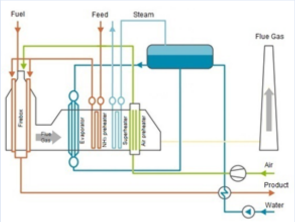
Centralized cracking using gas infrastructure

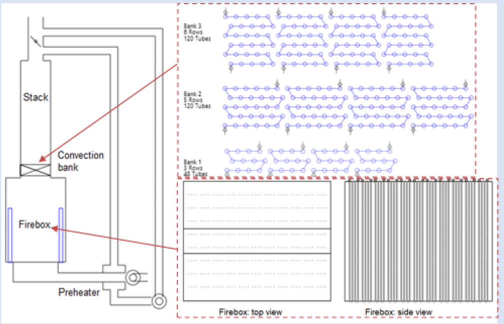


Centralized cracking for large scale H_2 recovery from ammonia – Example of a 200ton/day Hydrogen plant

Large-scale cracker design

- Design of a 110 MW NH_3 fired cracker
- Overall thermal efficiency of 93%
- NH_3 conversion rate of 85%
- Fueled with NH_3/H_2 blend
- Steam cogeneration at 40 bars

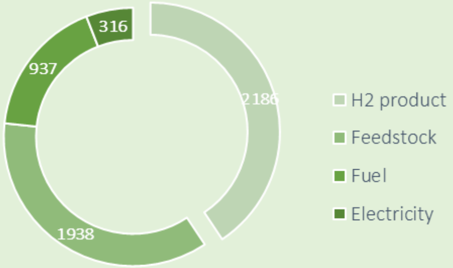


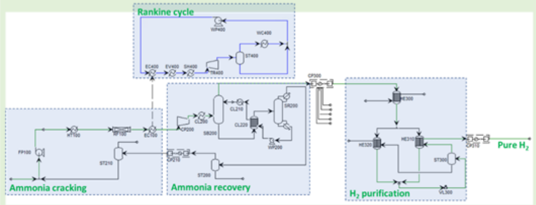


Large-scale plant design

- Design of a 200 MTPD hydrogen plant
- Hydrogen delivered at 250 bar
- High hydrogen purity 99.97%
- Overall efficiency of 68%$_{LHV}$
- 15 MW electricity cogeneration

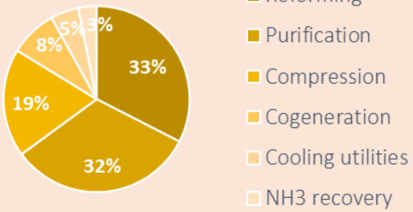
Energy balance in GWh/year



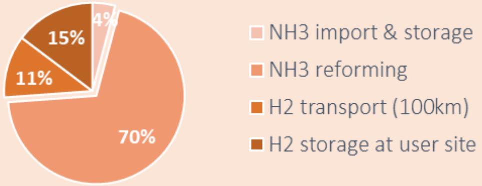


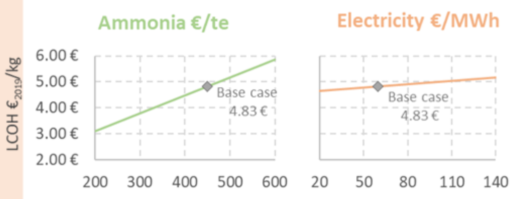
LCOH and transport costs

Equipment cost breakdown

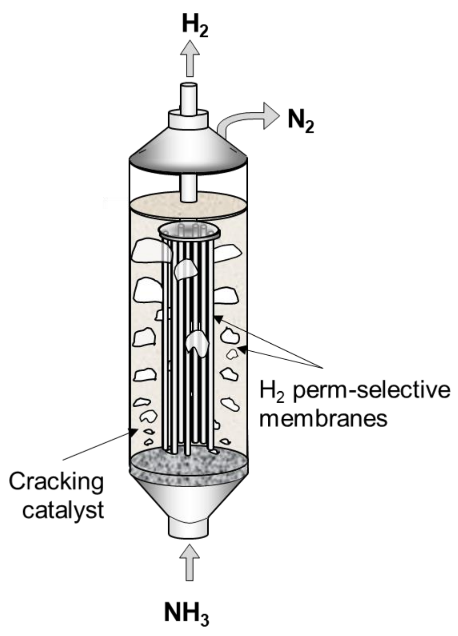


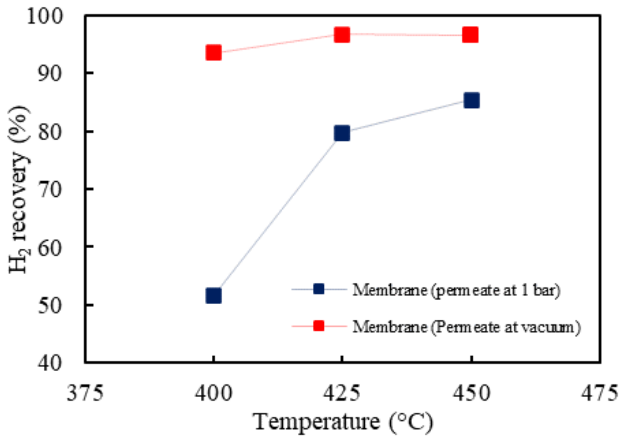
H_2-to-user site cost breakdown

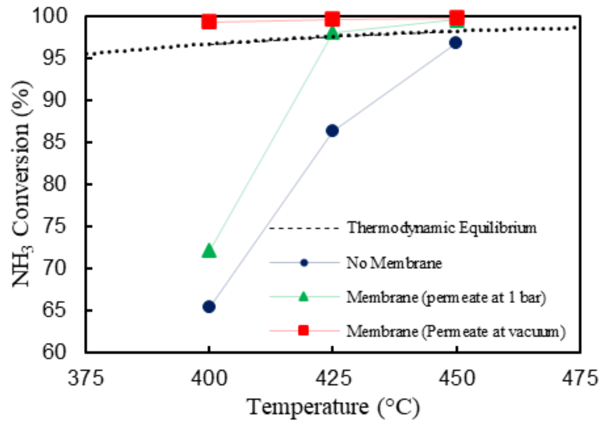




Decentralized Ammonia cracker : on-site and on-board Hydrogen generator







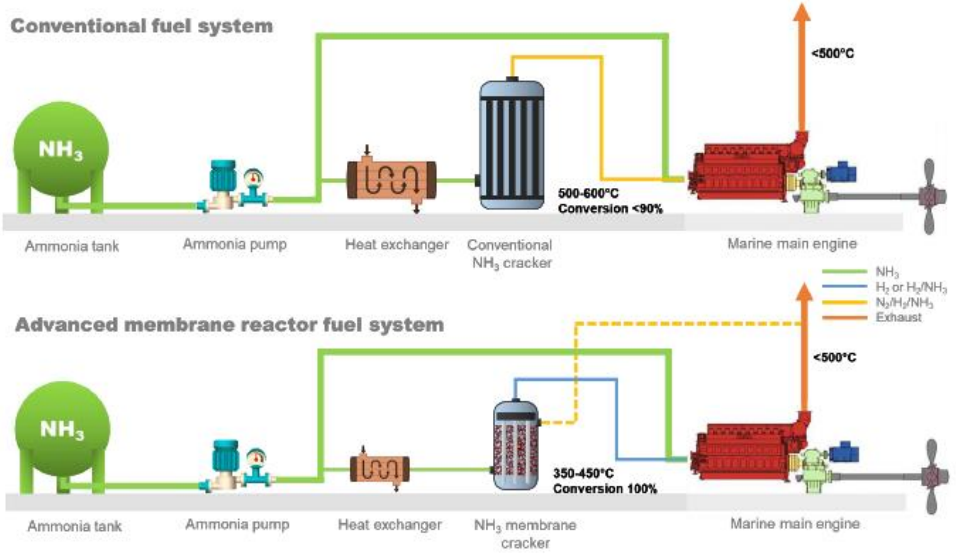
- Simpler system to generate pure hydrogen locally in a single step at the purity required for Hydrogen vehicles (ISO 14687-2)
- System producing up to several tons per day of hydrogen from ammonia with lower footprint
- Improved economics with higher efficiency due to higher conversion and low operation temperature compared to commercial solutions.
- Experimental validation demonstrates almost full conversion of NH_3, even at 400 ℃, and in all the cases beyond equilibrium. Typical cracker operates at close to 700°C.
- First demonstrator being built by ENGIE Lab CRIGEN and TU/Eindhoven - Operation startup : end 2021
- Commercialization in the near future by H2SITE

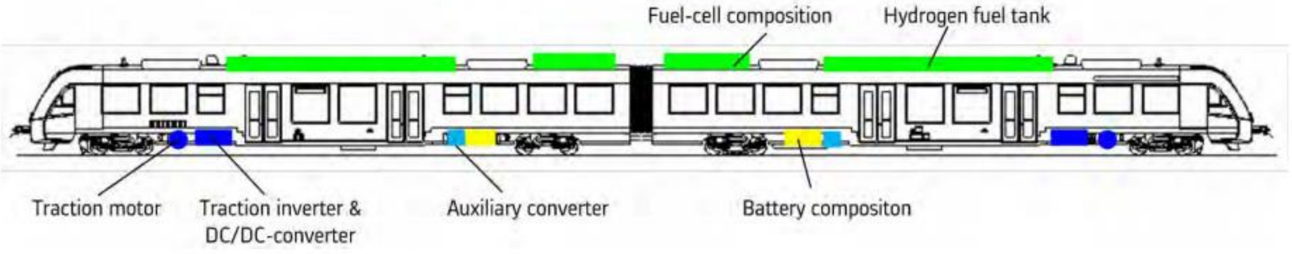
H_2 PRODUCTION VIA AMMONIA DECOMPOSITION IN A CATALYTIC MEMBRANE REACTOR; V. Cechetto, L. Di Felice[1], J.Medrano[1,2], C. Makhloufi[1,3], J. Zuniga [1,4], F.Gallucci[1]

On-board hydrogen generation for heavy transport

	FC power	H_2 storage required	NH_3 equivalent
Truck class 8 (line haul)	300-450kW	79kg H2 at 350 bar / 80 tanks 8m^3 occupied / 2,7tons	650L NH_3 at 8,6 bar
Train	400kW	120 kg at 350 bar / 130 tank 13 m^3 occupied / 4,3 tons	1m3 at 8,6 bar
Mining truck	0,9 – 3MW	≈1000kg at 350 bar/ 700 tank 70m3 occupied/ 23 ton	8 m3 at 8,6 bar
Shipping	Up to 80 MW		

** Considering 12kg/100km per class 8 truck, rough hypothesis for mining truck*






Thanks for your attention
Any questions

akuo
Entrepreneurs by nature

BESS Optimal Cycling

Aging vs Revenues

Tancredi Peraino
Akuo Energy : Project Manager - Hybrid Power Systems

Agenda

1. Akuo Energy
2. Optimal Cycling
3. Battery Degradation: main factors and aging model
4. Revenues and Penalties for Grid Connected BESS
5. Cycling modelling
6. Optimisation Algorithm
7. Merchant Application
8. Conclusion

Akuo Energy

Founded in **2007**, Akuo develops worldwide **renewable energy projects**

Development → Contracts & Financing → Construction → Operation

In 2014, Akuo launched the **development & sale** of renewable energy **solutions** to third parties.

- Solar GEM
- Storage GEM
- Solar Tiles
- Floating Solar
- Hydrogen

261 M€
TOTAL GROUP REVENUES AS OF END 2019

1,3 GW
CAPACITY IN OPERATION AND UNDER CONSTRUCTION AT END OF 2020

€2.6 BN
CUMULATIVE INVESTMENT BY THE GROUP SINCE INCEPTION AS OF END 2020

>5 GW
OF PROJECTS IN DEVELOPMENT AT THE END OF 2020

Optimal Cycling

Why?

BESS will rapidly pass from basic operation to **concurrent bidding** and participation in **multiple markets**

How?

Elaborate the optimal BESS (or hybrid) dispatch strategy to maximise the project's NPV

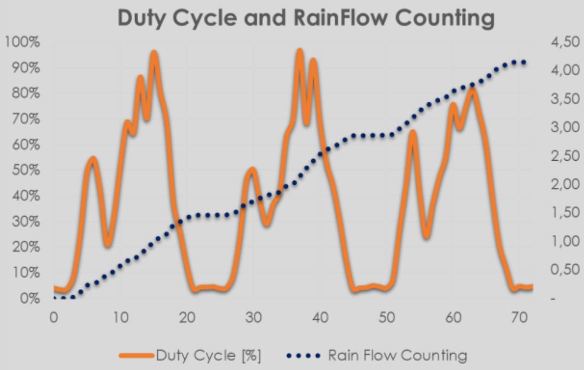
Battery Degradation

Stress Factors:

DOD SOC C-rate Temperature

Aging Model:

Cycle Analysis



Degradation Model

Miner's rule

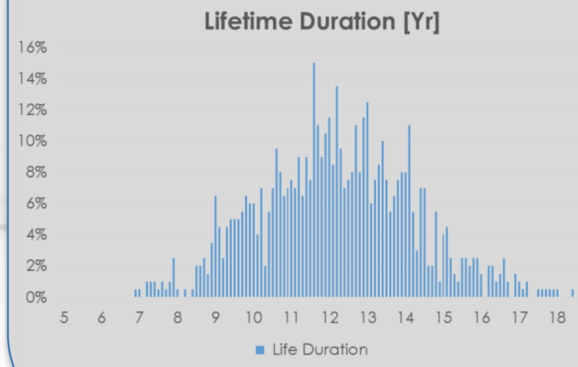
Life consumption

$$LC = \sum_{j=1}^{K} \frac{n_j}{N_{fj}}$$

# of cycles to failure

$$N_{cycle}(SoC, DoD) = \left(\frac{C_{fade}}{a * e^{-b*SOC} * DoD^{c}} \right)^2$$

Lifetime Estimation



BESS Revenue Sources

akuo
Entrepreneurs by nature

Capacity Market

Balancing Authorities remunerating grid - connected assets to ensure capacity [$/MW/h]

Ancillary Services Market

Grid Operators contracting fast-response and regulating reserve [$/MW-MWh-mileage]

Merchant Market

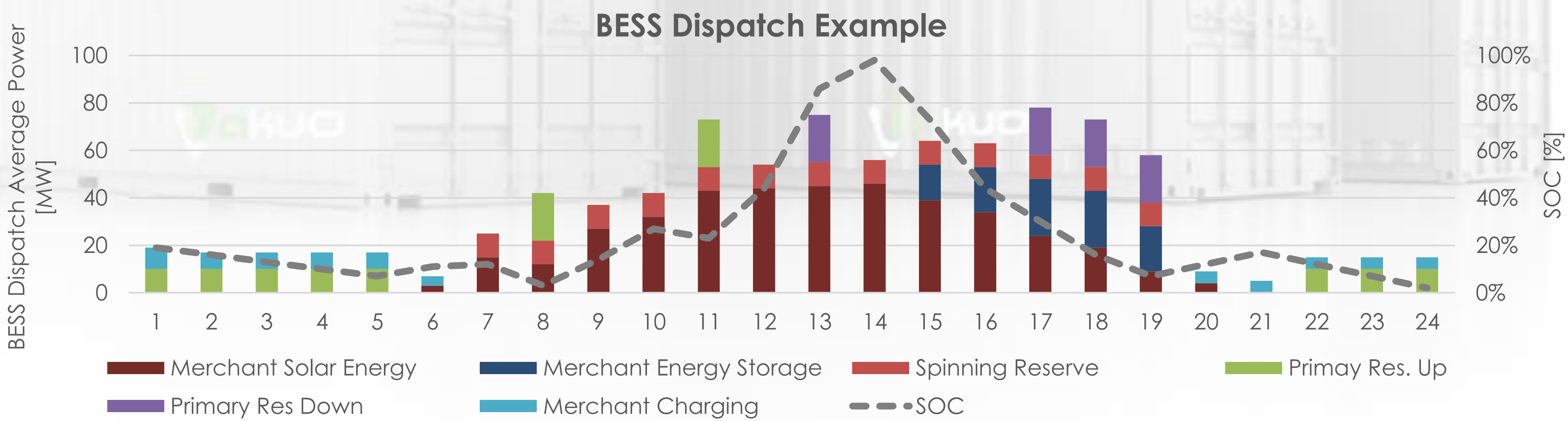
Hourly or sub-hourly day-ahead and intraday markets for energy trade [$/MWh]

Grid Support Markets

Grid operator remunerating for spinning reserve, non-spin or contingency reserve.[$/MWh]

Renewable Arbitrage

Avoid curtailment and optimise the economical valorisation of energy [$/MWh]



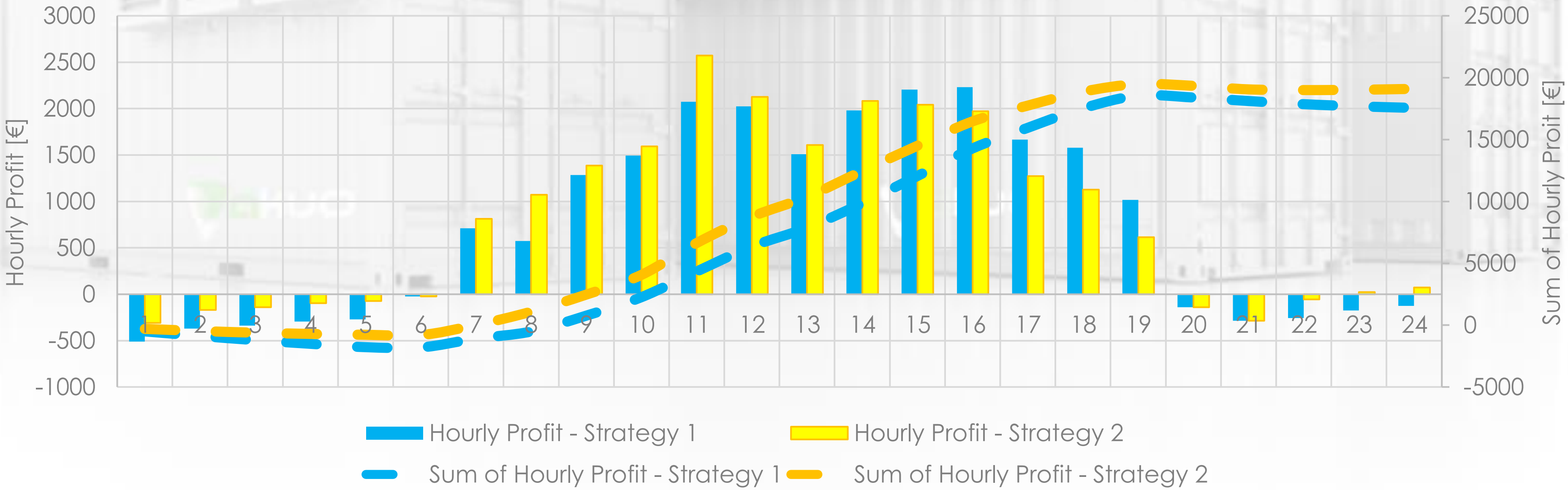
Cycling Modelling

Cycle Economics

$$Cost_{cycle}\,[\$] = LC_{cycle} * \left(C_{investment} + \sum_{n}^{N} \frac{C_{O\&M}}{(1+r)^n} + \sum_{n}^{N} \frac{C_{charging}}{(1+r)^n} + \frac{C_{disposal}}{(1+r)^{N+1}}\right)$$

$$\text{Revenue}_{\text{cycle}}\,[\$] = \sum_{n}^{N} \frac{R_{capacity}}{(1+r)^n} + \sum_{n}^{N} \frac{R_{discharging}}{(1+r)^n} + \sum_{n}^{N} \frac{R_{ancillary}}{(1+r)^n} + \sum_{n}^{N} \frac{R_{grid\ support}}{(1+r)^n} + \sum_{n}^{N} \frac{R_{rwe\ revalorisation}}{(1+r)^n}$$

$$Profit_{cycle}\,[\$] = Revenue_{cycle} - Cost_{cycle}$$



Optimisation Problem

The optimization problem aims at **maximize** the total **NPV** of the **profit** expected from the **BESS** or **hybrid system** by evaluating the best trade off between the **multiple markets 'revenues** and the **BESS degradation**

Inputs

- Markets' Prices Forecast
- Design & Economics
- Technical Inputs
- RWE Forecast

Cycle Optimisation Problem

Objective Function

$$\max Profit_{day} =$$
$$= \sum_{t=1}^{n} Profit_t(P_{S_1}, \dots, P_{S_3}, SOC, DoD, P_{ch})$$

Decision Variable

$$Power\ for\ each\ services:\ P_{S_1}, \dots, P_{S_3}$$
$$Power\ for\ charging:\ P_{ch}$$
$$Power\ from\ RWE:\ P_{RWE}$$

Outputs

$$Profit_{lifetime} = \sum_{d=1}^{lifetime} Profit_{day}$$

Outputs

- Project Economics
- Strategy Selection
- BESS Performances

Constraints

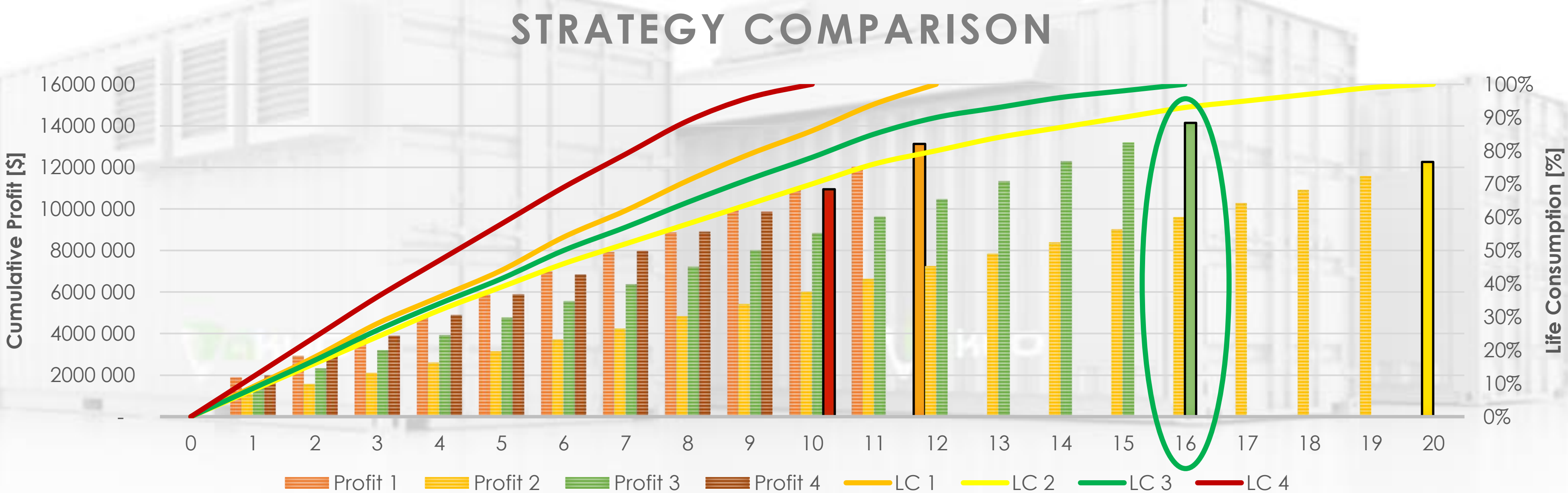
Taxes - Technical Constraints - Market Functioning & Regulation – Grid Operator Requirements

Merchant Application

CAISO Market:

Day Ahead & Real Time Energy Market (15 min time step)

- Day-ahead M. → bids from D-7 days until D-1
- Real Time M. → from 1:00 p.m. of D-1 until 1h15 before the trading hour



The **strategy 3** presents the best trade off between the battery consumption and the cumulated revenue

Conclusion

Akuo Entrepreneurs by nature

Model	Build and update the BESS dispatch and operational model considering the battery degradation as a cost
Revenue	Integrate revenues streams, constraints and calendar of the local electricity market
EMS	Develop and update a smart EMS capable of accurate forecast and optimal decision making
Market	Screen all the markets to assess their maturity and estimate the shortfalls and market delay for optimal prospection strategy

Akuo — Entrepreneurs by nature

Thank you for your attention!