ENVISION

Examining the business incentives for investments in coupled wind - storage systems

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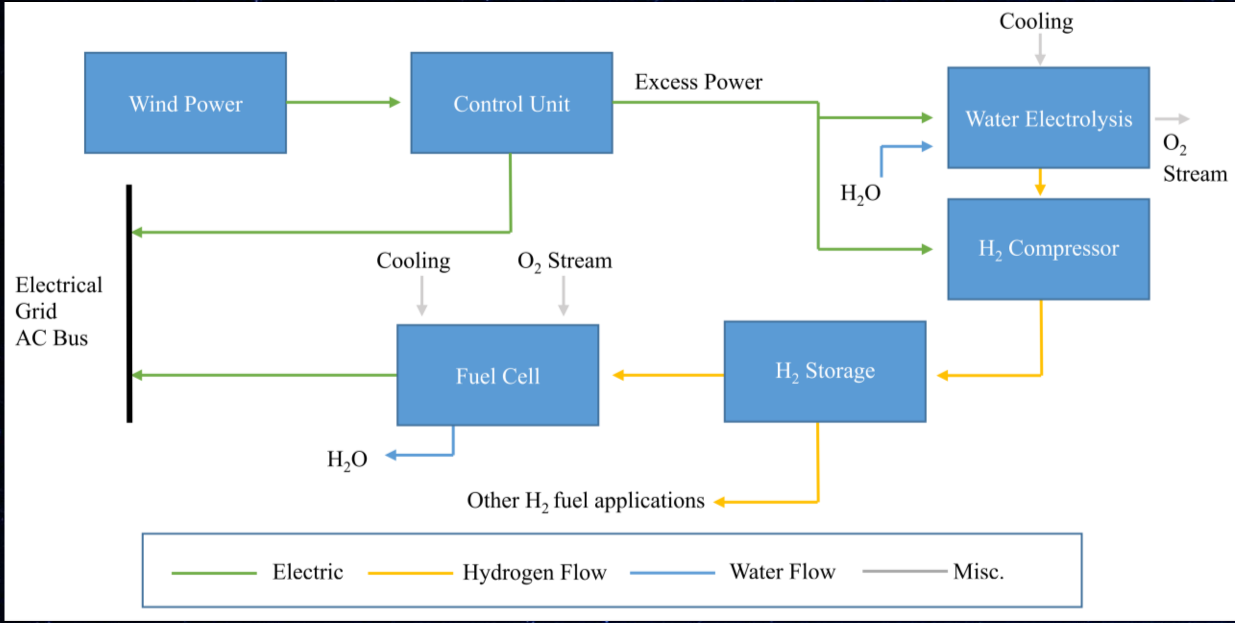
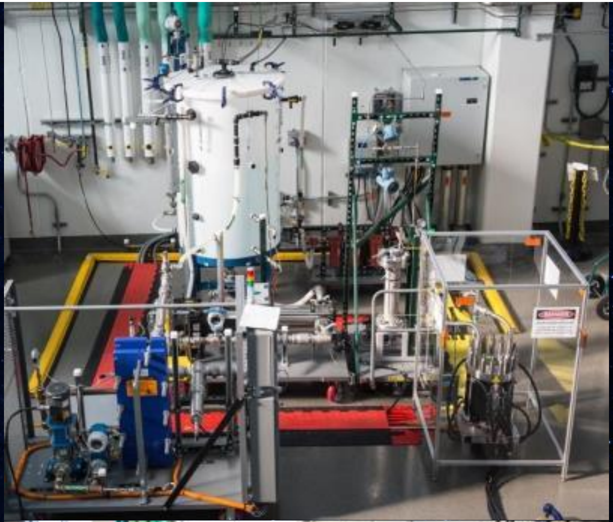
Outline

- Challenges mitigating renewable variations, challenges decarbonizing transportation sector
- Electrolysis are flexible loads that can be used to produce hydrogen and provide benefits to the electric grid
- The business incentives for storage applications
- Hydrogen can be sold to a variety of end uses
- Transportation offers unique benefits, particularly MD/HD because of ideal match with hydrogen for range and refill time.

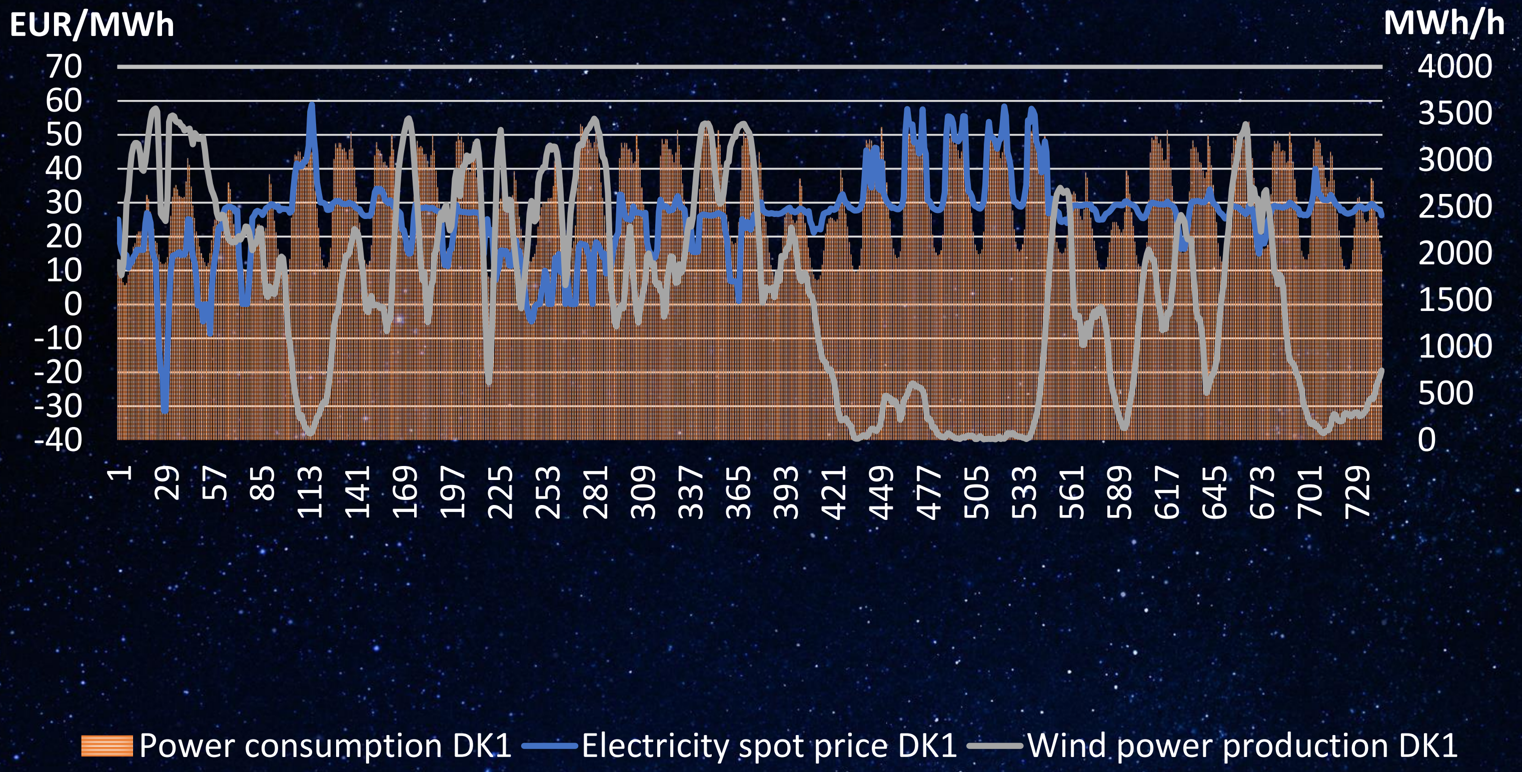
Wind energy storage configuration based on hydrogen technologies





Apostolou & Enevoldsen, 2019

What is it all about?



Hou et al, 2017

Challenges

- Varying electricity prices is a consequence of the global electrification and transition towards societies powered by renewables

- Price variations or volatility is partly due to renewable intermittency

- Various scientific proposals have included storage applications to **1)** control the fluctuations, and **2)** to optimize the business potential of wind farms.

- However, few, if any have adequately investigated the difference of storing electricity to apply it for different purposes

Purpose

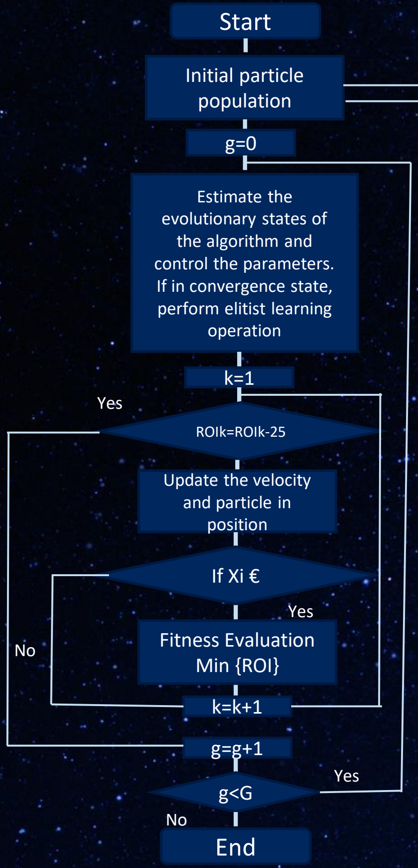
Examining Various Storage Application and Strategies

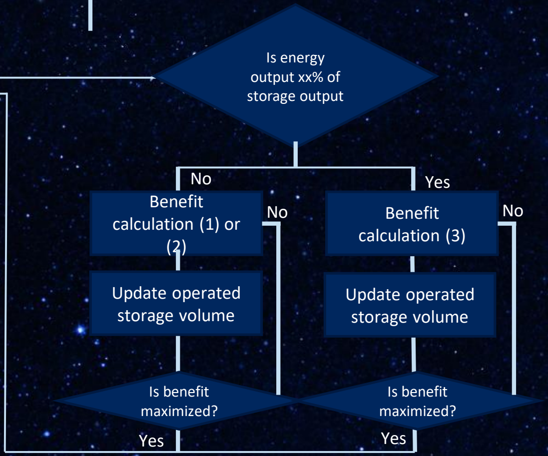
- **Benchmark:** Wind farm without any storage application
- **Configuration 1 (P2P):** Wind farm with P2H for electricity market arbitrage
- **Configuration 2 (P2P+P2G)** Wind farm with P2H for generating hydrogen
- **Configuration 3 (P2P):** Wind farm with P2B for electricity market arbitrage

*P2H = Power-to-Hydrogen
*P2B = Power-to-Batteries

Optimization Methods

Outer Layer: Component Selection | Inner Layer: Operational Optimization





(1) $$\max\left[I_r^n(x,y)\right] = \max\left\{\sum_{t=1}^{T} EP_t\left[E_t^W - E_t^H(x_t)\right]\right\}$$

(2) $$\max\left[I_r^n(x,y)\right] = \max\left\{\sum_{t=1}^{T} EP_t\left[E_t^W - E_t^H(x_t)\right] + D_H O_e \frac{P_H}{\eta_{EL}}(T-1)S_H\right\}$$

(3) $$\max\left[I_r^n(m,y)\right] = \max\left\{D_H O_e \frac{P_H}{\eta_{EL}}(T-1)S_H - \sum_{t=1}^{T} EP_t P_t\right\}$$

- The approach is inspired by Hou et al (2017)
- We will couple the sequential quadratic programming and the adaptive particle swarm optimization.
- The decision process can be simplified to follow the structure introduced in the figure.

Results

<u>Various scenarios were established and examined:</u>

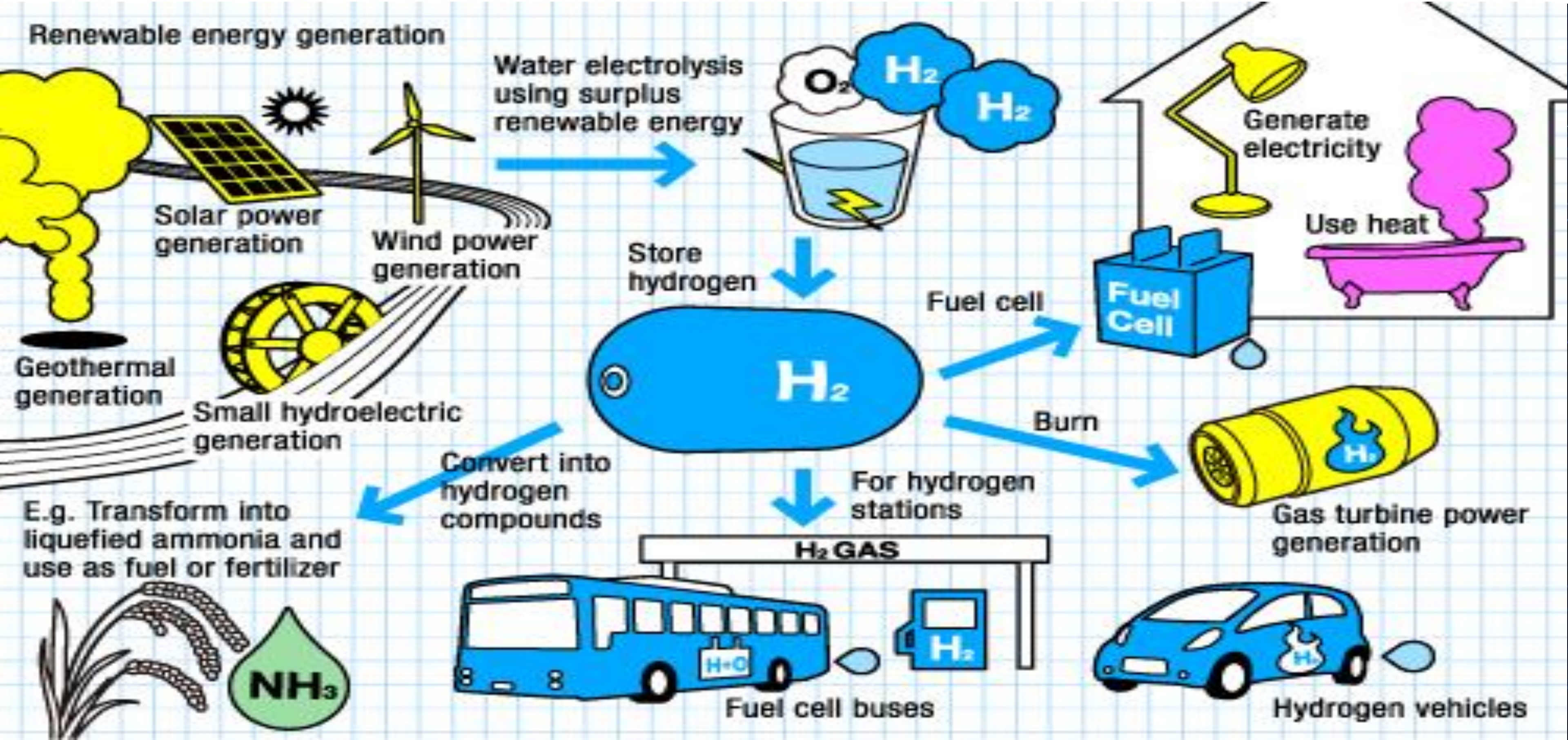
- **Scenarios I:** Power-to-Power (P2P) using Electrolyser and Fuel Cell
- **Scenario II- IV:** P2P and/or Power-to-Gas (P2G) depending on the electricity market and wind farm production
- **Scenario V:** P2P using lithium-ion Batteries

* 2, 5 and 9€/kg for scenario II, III and IV, respectively

Results

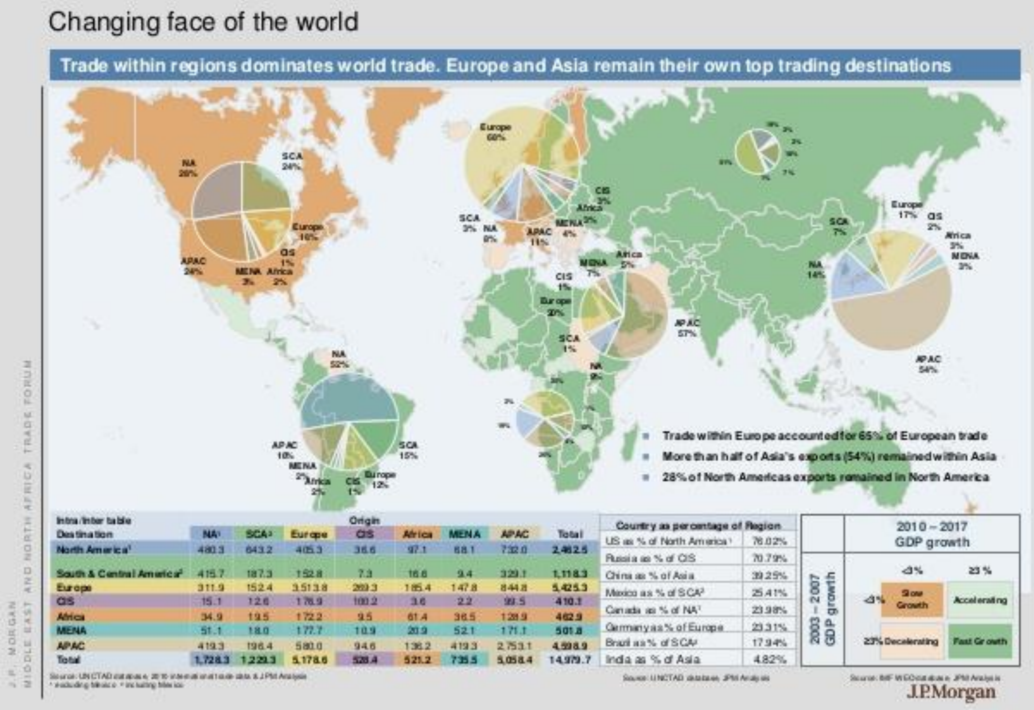
	Return on Invest-ment (years)	Total benefits in NPV (M€/yr)	Hydro-gen price (€/kg)	NPV of total profits from hydrogen market (M€/yr)	NPV of total profits from electricity market (M€/yr)	NPV of total cost of energy from electricity market (T€/yr)	NPV of electro-lyzer cost (M€)	NPV of storage cost (T€)	NPV of fuel cell cost (M€)	NPV of O&M cost (T€/yr)
BENCHMARK	/	4.15	/	0	4.15	0	/	/	/	/
Scenario I	Inf	4.15	0	0	4.15	0	0	0	0	0
Scenario II	24.4	4.61	2	0.47	4.14	2.71	5.72	14.38	/	178.4
Scenario III	5.5	7.02	5	2.91	4.11	7.65	12.63	27.87	/	397.3
Scenario IV	***2.6***	***13.13***	9	***9.10***	4.02	***42.33***	***20.82***	***46.71***	/	***658.5***
Scenario V	6.1	4.61	/	/	***4.61***	/	/	0.04	/	/

Appliance


Renewable energy generation
Water electrolysis using surplus renewable energy
O_2
H_2
H_2
Generate electricity
Use heat
Solar power generation
Wind power generation
Store hydrogen
Fuel cell
Fuel Cell
Geothermal generation
H_2
Small hydroelectric generation
Burn
Convert into hydrogen compounds
For hydrogen stations
E.g. Transform into liquefied ammonia and use as fuel or fertilizer
Gas turbine power generation
H_2 GAS
H_2
NH_3
Fuel cell buses
Hydrogen vehicles

Goods movement

- Focus on opportunity for goods movement in Europe/U.S.
  - Most trade with a given country/region happens within that country/region



Intra/Inter table Destination	Origin NA[1]	SCA[2]	Europe	CIS	Africa	MENA	APAC	Total
North America[1]	480.3	643.2	405.3	36.6	97.1	68.1	732.0	2,462.5
South & Central America[2]	415.7	187.3	152.8	7.3	16.6	9.4	329.1	1,118.3
Europe	311.9	152.4	3,513.8	269.3	185.4	147.8	844.8	5,425.3
CIS	15.1	12.6	178.9	100.2	3.6	2.2	99.5	410.1
Africa	34.9	19.5	172.2	9.5	61.4	36.5	128.9	462.9
MENA	51.1	18.0	177.7	10.9	20.9	52.1	171.1	501.8
APAC	419.3	196.4	580.0	94.6	136.2	419.3	2,753.1	4,598.9
Total	1,728.3	1,229.3	5,178.6	528.4	521.2	735.5	5,058.4	14,979.7

Source: UNCTAD database, 2016 international trade data & JPM Analysis
[1] excluding Mexico [2] including Mexico

Country as percentage of Region	
US as % of North America[1]	76.02%
Russia as % of CIS	70.79%
China as % of Asia	39.25%
Mexico as % of SCA[2]	25.41%
Canada as % of NA[1]	23.98%
Germany as % of Europe	23.31%
Brazil as % of SCA[2]	17.94%
India as % of Asia	4.82%

Source: UNCTAD database, JPM Analysis

2003 – 2007 GDP growth \ 2010 – 2017 GDP growth	<3%	≥3%
<3%	Slow Growth	Accelerating
≥3%	Decelerating	Fast Growth

Source: IMF WEO database, JPM Analysis

J.P.Morgan

Goods Movement

Battery Electric

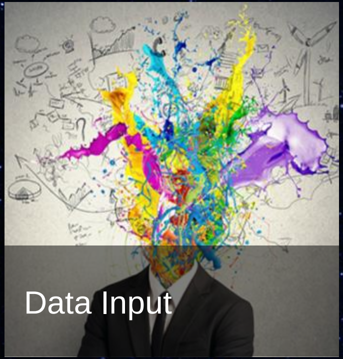
Tesla, Cummins, Thor
Lower cost of ownership
No emissions
~300 - 500 mile range

Hydrogen Fuel Cell

Toyota, Nikola
Toyota ~ 200 miles
Nikola ~ 1200 miles (2020)

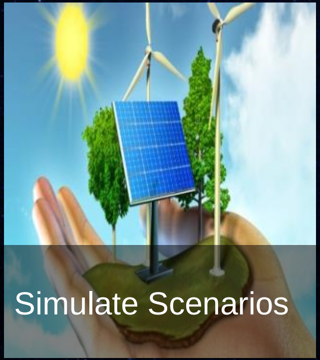
Wide range of vehicle types and classes

Suggestion: Software for Selection and Optimization



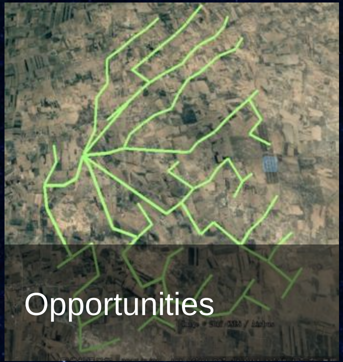
Data Input

- Determine peaks in Electricity market
- Identify storage technologies



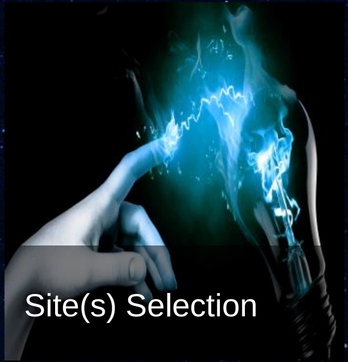
Simulate Scenarios

- Determine storage technology
- Identify barriers



Opportunities

- Grid Connections
- Area project development
- Re-consider storage technologies



Site(s) Selection

- Deliver clean and stable energy
- Boost the investment

?

Outlook

- There is a need to understand how the delivery pathways of electrolyzed hydrogen would impact the business case.
- What happens when considering ancillary grid services (Could we establish a business case only by reducing grid penalties)?
- Batteries can still be considered a vital gateway technology, and furthermore very applicable if the target is P2P
- What about offshore wind farms?
- Should storage technologies be considered in wind turbine control design?

Technological Insights and Data Applied

Wind Turbines:

Type	Custom WTG
Cut-in Wind Speed	3 m/s
Rated Wind Speed	17 m/s
Cut-out Wind Speed	25 m/s
Rotor Diameter	110 m
Rated Power	3.5MW

Electrolyzer:

Type	Alkaline		Alkaline		PEM (2015)	
Producer	NEL Atmospheric pressure (S1)		HYDROGENICS (S2)		Proton Onsite (S3)	
Plant size (MW)	10	100	10	100	10	100
Average System Efficiency during lifetime (kWh/Nm^3)	4.9	4.9	5.5	5.5	6.1	6.1
Technical lifetime (years)	25	25	25	25	25	25
Turnkey price (Million Euro)	9.30	84.03	17.20	148.64	9.65	64.08
Total O&M including stack exchange / 7th year (Thousand Euro)	510.67	4840	1297.33	12396	174.67	1162.67

Fuel Cell:

Type	Proton exchange membrane fuel cell
Capacity (kWe)	0.2-0.7
Technical lifetime (year)	15
Annual average electric efficiency (%, LHV)	35

Battery:

Type	lithium-ion
Capacity (MW)	10
Technical lifetime (year)	20
Average charging efficiency (%)	90
State of charge (SOC) lower limit (%)	10
State of charge (SOC) upper limit (%)	90
Battery cost ($/kWh)	273

Thank you!

Solving the Challenges for a Sustainable Future!

Dr. Peter Enevoldsen