What can Science Provide for Hydrogen Impementation

OCTOBER 22, 2018 | PROF. DETLEF STOLTEN

Franco-German Conference on Hydrogen

Paris

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IEK-3: Institute of Electrochemical Process Engineering

Hydrogen in the Energy Transition

Energy transition

- Scope
- Targets
- Timeline
- Constraints and Implications
- Barriers (from incumbents'' resistance via markets and regulations down to technologies)

Hydrogen

- Generation Technologies
- Transmission & Distribution and Storage Technologies
- Application Technologies
- **Hydrogen Safety**
- Hydrogen Energy Pathways w/r to efficiency and cost
- Hydrogen Markets @ Entry Level, Penetration Level and
- Hydrogen Energy Services
- Business and Citizen Participation Models
- Phase-in into Industry 4.0 and Extend to Energy 4.0
- Hydrogen as a tradeable commodity for sector coupling
- Economic and quantitative constraints
- Barriers

Introductory Remarks

- The simplest applicable energy pathways will in most cases turn out to be the most efficient, effective and cost effective

1. Direct use of power
2. Storage in batteries
3. **Hydrogen storage**
4. Methane storage
5. Liquid fuel production

Decreasing efficiency

- Power to chem comes in parallel
- Quantitative storage requirements will probably be much higher than we anticipate today
- All of the above mentioned storage options will be needed, owing to the limited applicability of the easier ones (e.g. liquid jet fuel for aviation)
- The complete energy chain needs to be considered for future decisions
- **Energy security requires large amounts of storage – as we have implemented today**

Hydrogen Relevant Specifics of the Energy Transition

Ramifications of the Energy Transition

- After the transition period energy should **not** be **more expensive** than today
- **Limited emissions** shall be reduced
- Electricity, fuels and heat must be available at **high reliability**
- **All energy sectors** need **to be addressed to achieve these goals**
- **Hydrogen is required** for **sector coupling**
- Teratogenic, carcinogenic and poisonous substances shall be avoided
- Radiative forcing to be considered (e.g. methane > 20) for new energy pathways
- **Spatial restrictions** in installing renewable energy compel high efficiency of energy pathways
- Dichotomy between a **very distributed** (e.g. household PV) vs. **very centralized** system (off-shore wind farms and coastal on-shore wind power generation)
- Long-term storage for providing
  - Energy security
    - Back-up for sustained low energy input, i.e. **Flaute** of >14days
    - **“90 day” or so energy reserve** for critical areas, e.g. transportation
  - Shifting seasonal energy overproduction

The Saga of Rising Fuel Prices

If the Energy Transition is successful in some major countries

- **Conventional fuel prices will drop** toward their marginal production cost util a new price level is established; US$5/barrel can be assumed the lowest marginal cost (Saudi Arabia)
- **Finally** that price level will decide over new **explorations** which might **taper off**
- Only **then oil prices might skyrocket**

- => **high incumbent market forces to be expected if no counter measures taken**

R&D for effective materials, components and systems at low cost is crucial

Creating an RE Market

Hydrogen Markets @ Entry Level, Penetration Level and

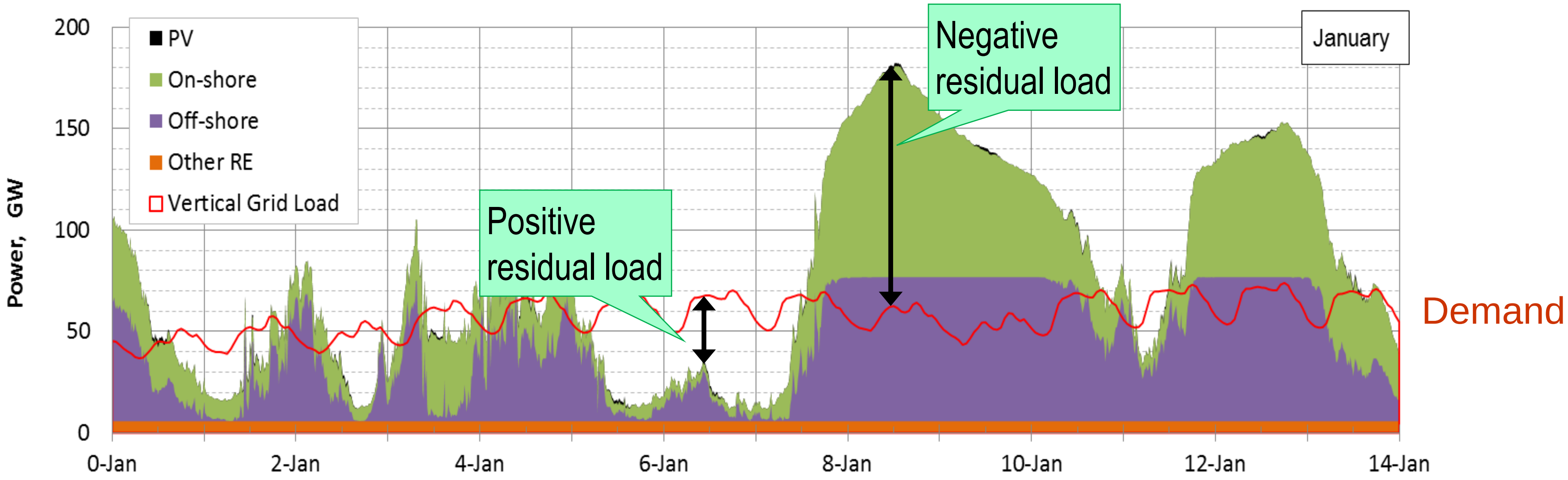
- Hydrogen Energy Services
- Business and Citizen Participation Models
- Phase-in into Industry 4.0 and Extend to Energy 4.0
- Hydrogen as a tradeable commodity for sector coupling

Interdisciplinary research on business models, legal barriers, digitilization and energy technologies is required

Business models will partly be technology inspired and technological developments will inspire new business models

Hydrogen in the Energy System

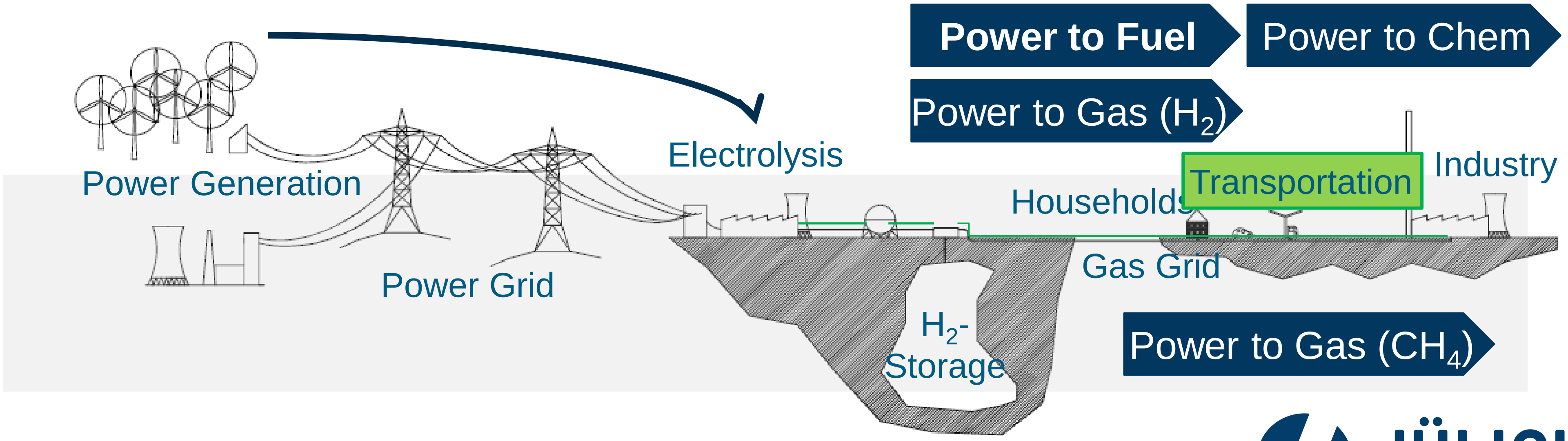
Excess Power is Inherent to Renewable Power Generation



Negative residual load

Positive residual load

Demand



Power to Fuel

Power to Chem

Power to Gas (H_2)

Power to Gas (CH_4)

Power Generation

Power Grid

Electrolysis

H_2-Storage

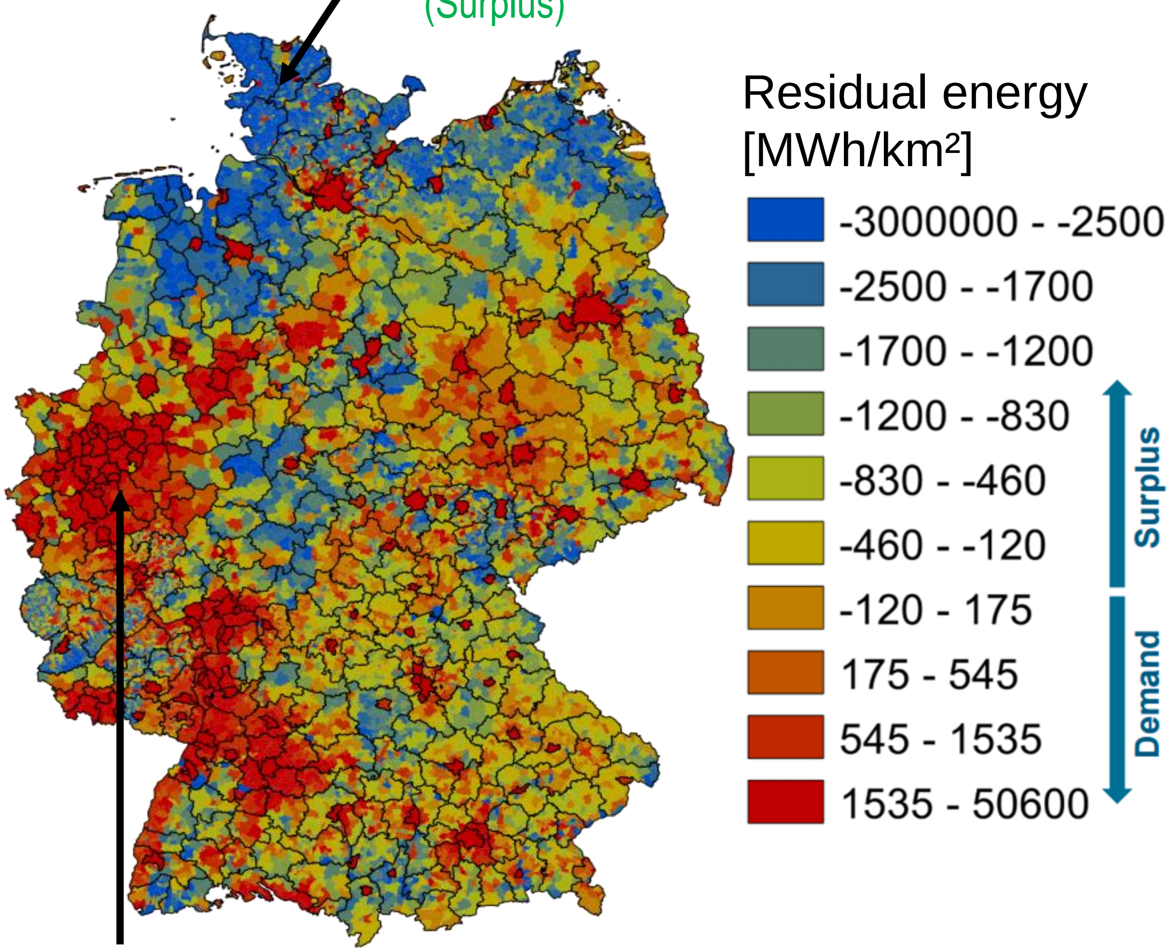
Households

Transportation

Industry

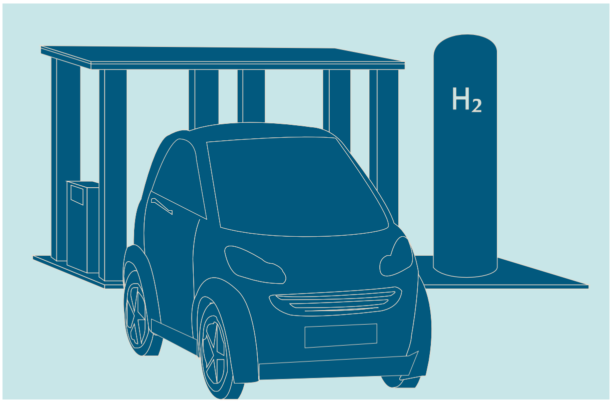
Gas Grid

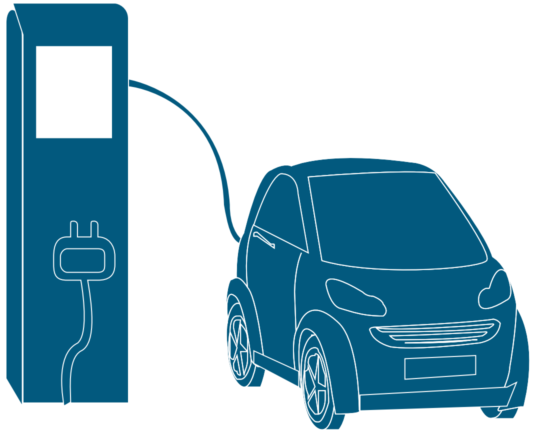
Linking the Power and the Transport Sector



Negative residual energy
(Surplus)

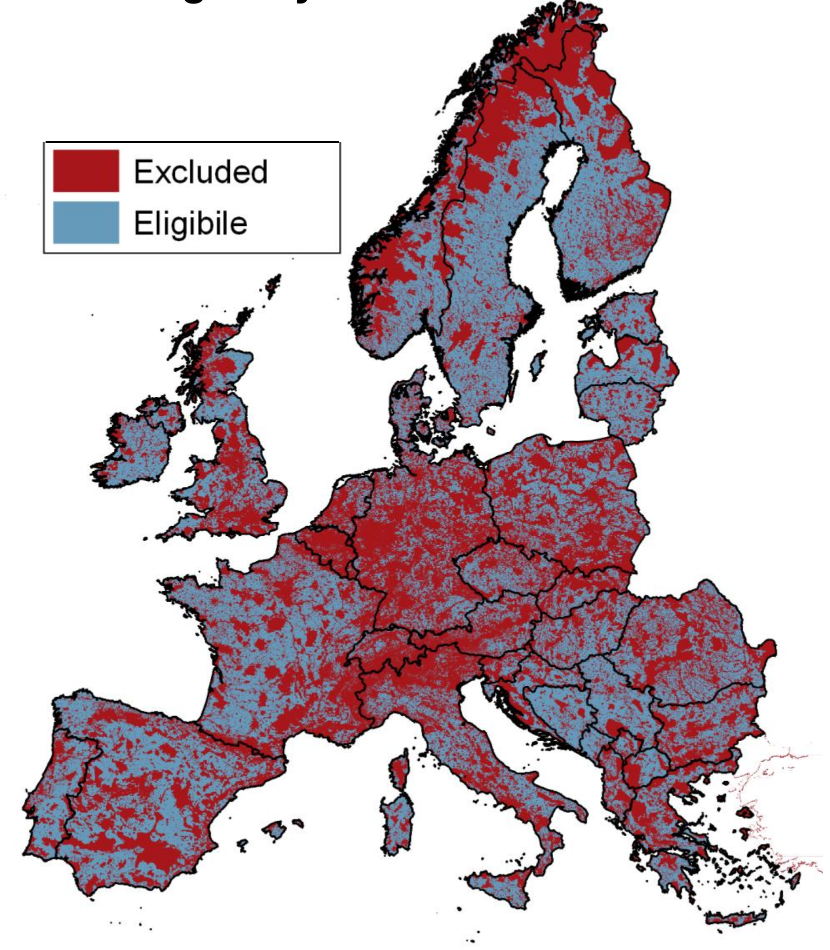
Positive residual energy



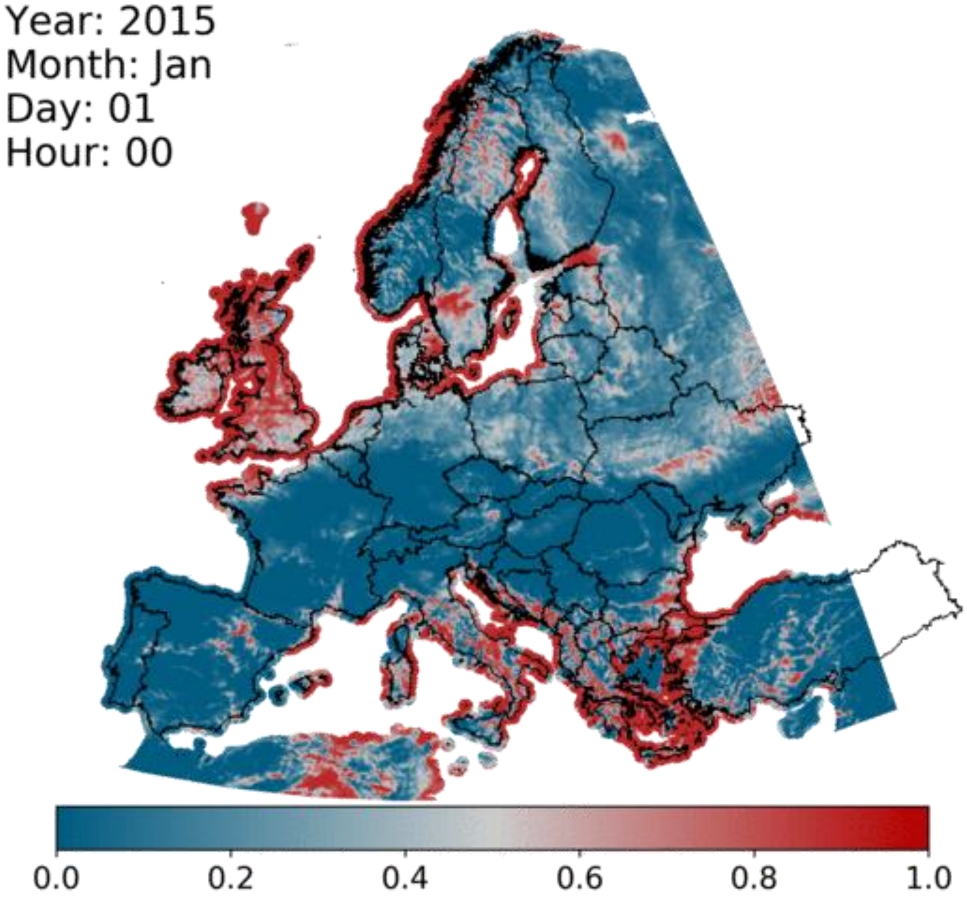


Case in Point: Wind Power Generation in Europe

Land Eligibility Onshore Wind



Resulting wind electricity generation in Europe



non **generation** **ma**

Central Europe emerges as a pretty homogenous climate region
=> storage rather than power transport needed to secure energy supply

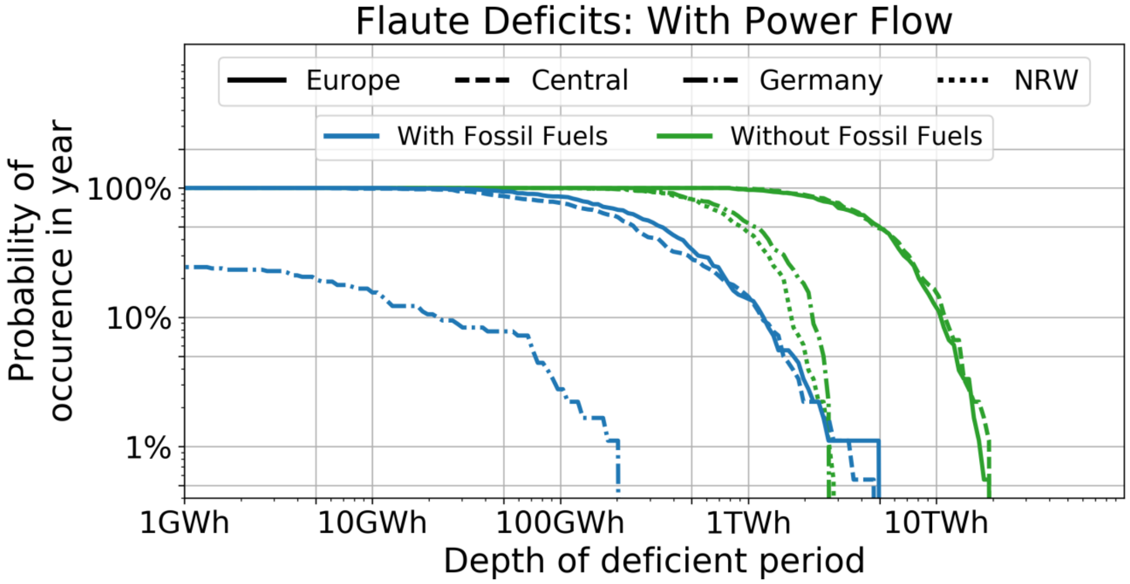
[1] Robinius, M. et al.: Linking the Power and Transport Sectors—Part 2: Modelling a Sector Coupling Scenario for Germany. Energies, 2017. 10(7): p. 957. **[2]** Ryberg, D., M. Robinius, and D. Stolten, Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe. Energies, 2018. 11(5): p. 1246

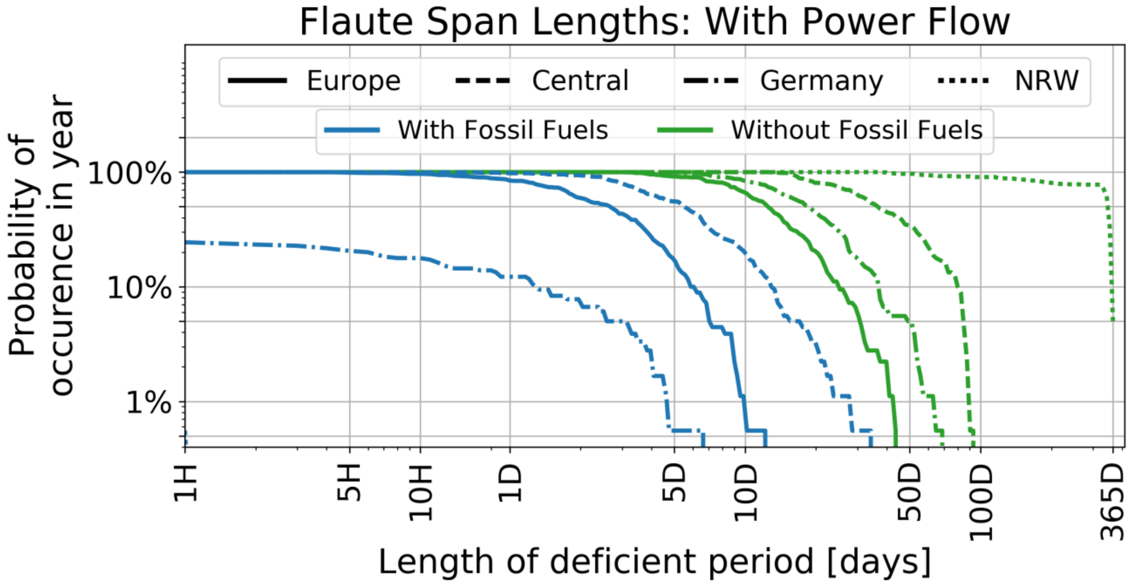
Dunkelflaute Investigation: VRES vs. Demand

- Without fossil fuels…
  - **72 hour flaute is guarenteed**
  - NRW full-year-flaute in 5.0% of years
- With fossil fuels…
  - NRW and Germany observe no flaute in 99.4% and 75.6% of years
- **~10x increase** in flaute spans and deficits by adding grid dynamics
  - Depends on allowed occurrence
- Central region shown to have the longest flaute spans
- Central and Europe have similar deficits

Maximal flaute size in days and TWh

	w/ Fossil		w/o Fossil	
	Span	Deficit	Span	Deficit
NRW	1 Hr	<0.001	>365	2.8
Germany	6.6	0.20	68.7	2.7
Central	34.2	4.6	93.1	19.1
Europe	12.2	4.9	43.6	19.1

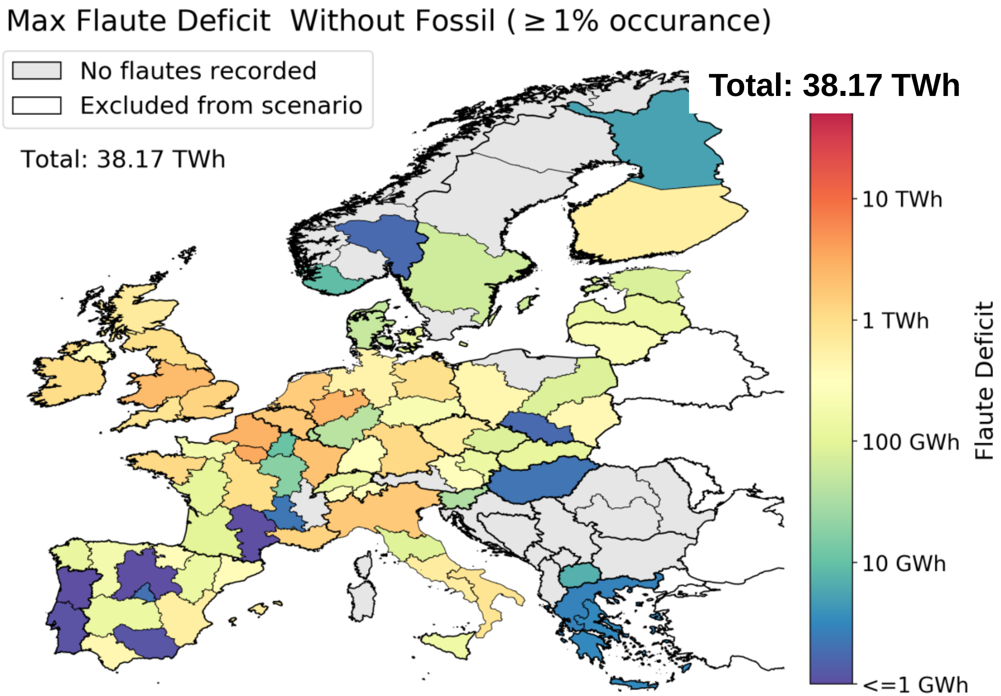




Dunkelflaute Investigation: Regional Overview With Grid Dynamics

- Even with fossil fuels, **Paris** is within a full-year-flaute for 6.7% of years
- If all regions supply their own storage, ‘worst case’ storage requirement rises to **8.89 TWh** with fossil fuels, and **38.2 TWh** without
- Countries with the highest need for storage: **United Kingdom** (3.65 TWh with f.f. / 6.48 TWh without f.f.), **France** (3.33 / 12.0), and **Germany** (0.26 / 5.77)
- Largest flaute found in different years for different regions (**no clear trend**)

Max Flaute Deficit Without Fossil (≥ 1% occurrence)



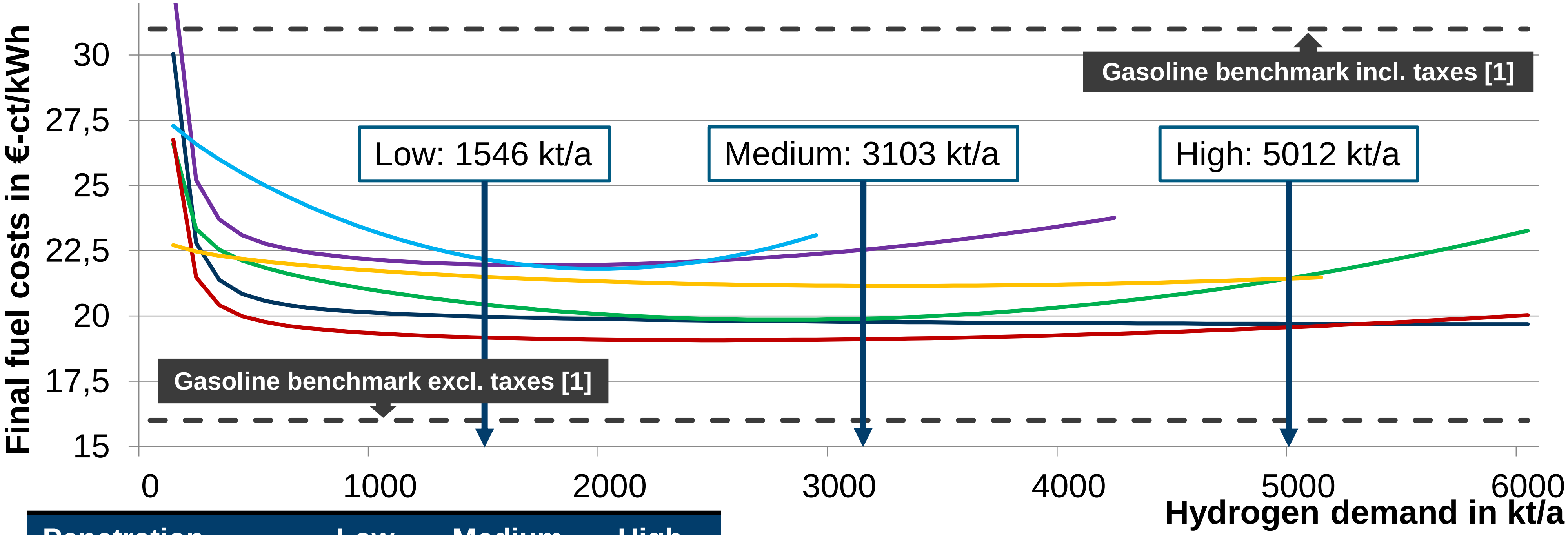
Total: 38.17 TWh

International Perspective of Hydrogen from Wind Power

Production
(Onshore wind, electrolysis)

Transport
(Pipeline, ship, truck)

Provision
(Fueling station)



Penetration	Low	Medium	High
Car / LDV / HDV*	25%	50%	75%
Local bus	30%	60%	95%
Local diesel train	50%	75%	95%
Forklift	30%	60%	95%

Hydrogen source regions

— Argentina	— Chile
— Iceland	— Norway
— United Kingdom	— Ireland

*** LDV / HDV:** Light / Heavy Duty Vehicle

Hydrogen End-use Technologies

Asian Fuel Cell Vehicles are in a Market Introduction Phase

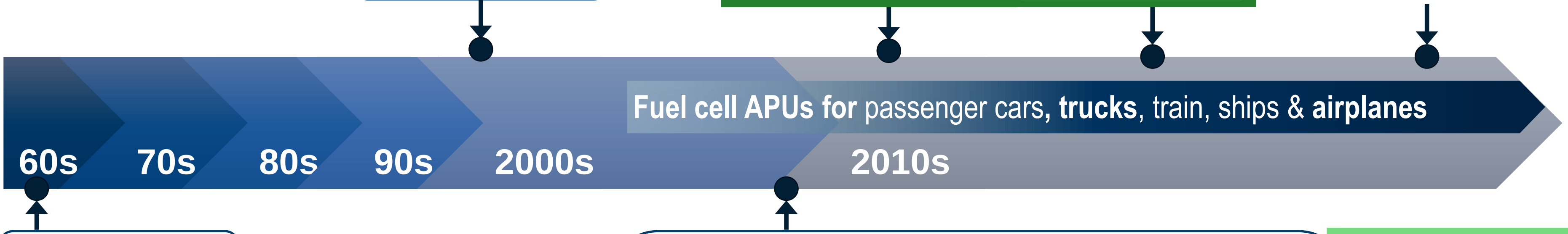
1999 MB NECAR 1 (H_2)


©Daimler

2012/ 13 Hyundai Nexo FCEV1st manufact. plant

2015 Toyota Mirai 2nd series prod.


©Toyota



1966 GM Electrovan (H_2, AFC)

©GM

First FCV

2008-2009

Small series for demonstration projects

MB B-Class F-Cell


©Daimler

GM HydroGen4


©GM

Honda FCX Clarity


©Honda

Aromatic membrane -30…95 °C

2017 MB GLC F-Cell

* First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use

MB: Mercedes-Benz; GM: General Motors

All cars with PEFC except GM Electrovan with AFC

H2Energy Drives Use of Fuel Cell Trucks

2016: H2Energy launches hydrogen logistic in closed loop for Coop Mineraloel AG [1]:

- **Zero-emission H_2 production** at hydropower plant in Aarau
- Fuel station for 350 and 700 bar **refilling of cars and trucks**
- Demonstration of **world‘s first** fuel cell truck

IAA 2018 [2]:
Hyundai announces cooperation with H2Energy

- **1000 FC trucks until 2023** on swiss market
  - 350 kW traction motor,190 kW FC
  - 32.86 kg hydrogen tank, 8.2 kg/100 km
  - ~400 km range
- 100% renewable production

[1] https://h2energy.ch/wp-content/uploads/2017/06/Factsheet_Lastwagen_D.pdf/
[2] https://insideevs.com/hyundai-launch-1000-hydrogen-trucks/

Efficiency is Crucial w/ Renewable Power: Hydrogen Delivers on W2W Efficiency

Battery vehicle (renewable electricity)

Efficiency:	80 % x 85 % = **68 %** (W2T) (T2W)
Vehicle cost:	⊖⊖
Fuel production:	⊕
Storage & distrib.:	⊖⊖⊖
Operating range:	low
Resources:	sufficient
Soot/NOx emissions:	none

Fuel cell vehicle (renewable electricity)

Efficiency:	63 % x 60 % = **38 %** (W2T) (T2W)
Vehicle cost:	⊖⊖
Fuel production:	○
Storage & distrib.:	⊕
Operating range:	medium
Resources:	sufficient
Soot/NOx emissions:	none

Combustion engine (CO_2-based fuels)

Efficiency:	70 % x 50 % x 25 % = **9 %** (H_2) (plant) (T2W)
Vehicle cost:	⊖
Fuel production:	⊖⊖
Storage & distrib.:	⊕⊕
Operating range:	high
Resources:	sufficient
Soot/NOx emissions:	medium

Combustion engine (bio-fuels)

Efficiency:	50 % x 25 % = **13 %** (W2T) (T2W)
Vehicle cost:	⊖
Fuel production:	⊖⊖
Storage & distrib.:	⊕⊕
Operating range:	high
Resources:	limited
Soot/NOx emissions:	medium

Today‘s
W2W Effciency
≈18%
w/ combustion
engines

T2W: tank-to-wheel
W2T: well-to-tank
W2W: well-to-Wheel
W2W = total efficincy

Summary of Technologies

Hydrogen Production

PEM Electrolysis

Property	**Today**	**Future**
η_{LHV} %	63	70
CAPEX €/kW$_{el}$	1500	500

TRL: 7-8

Advantages:
High gas purity
High load flexibility
High power density

Challenges:
Platinum Group Metals as catalysts

Alkaline Electrolysis

Property	**Today**	**Future**
η_{LHV} %	65	70
CAPEX €/kW$_{el}$	1000	580

TRL: 9

Advantages:
No rare metals in catalysts
Low specific cost
Established technology

Challenges:
Requires purification

Photoelectrolysis

Property	**Today**	**Future**
η_{LHV} %	10	18
CAPEX €/kW$_{el}$	2800 [1]	1200 [1]

TRL: 3-4

Advantages:
Standalone system
High gas purity
Less power electronics

Challenges:
High capital cost
Collecting hydrogen

PEM: Polymer Electrolyte Membrane **LHV**: Lower Heating Value **TRL**: Technology Readiness Level
CAPEX: Capital Expenditure

1: PV + PV Balance of Plant + Electrolysis

Hydrogen Storage

Salt Cavern[1]

Property	Today	Future
Density GJ/m^3	1.44	1.44
CAPEX €/kg$_{H2}$	9-15	6.6

TRL: 8-9

Advantages:
Long term storage
Low space demand
Low specific cost

Disadvantages:
Geological constraints

Projects:
Clemens Dome (US)
Tesside (UK)

Gaseous H_2 Bundle

Property	Today[2]	Future[3]
Density GJ/m^3	2.88	3,84
CAPEX €/kg$_{H2}$	800	600

TRL[2]: 8-9

Advantages:
Long cyclic lifetime
Established technology[2]
No geological constraints

Disadvantages:
High specific cost

Projects:
London (UK)
Oslo (NOR)

Liquid H_2 Tank

Property	Today	Future
Density GJ/m^3	8.5	8.5
CAPEX €/kg$_{H2}$	25	25

TRL: 9

Advantages:
Long cyclic lifetime
Established technology
No geological constraints

Disadvantages:
Requires liquefaction

Projects:
Vancouver (CAN)
London (UK)

TRL: Technology Readiness Level
CAPEX: Capital Expenditure

1: Cavern V = 500.000 m^3
P = 150 bar

2: Bundle pressure = 350 bar
3: Bundle pressure = 500 bar

Hydrogen Transport

H_2 Pipeline

Property	Today[1]	Future[2]
Capacity t_{H2}/h	2,4	245
CAPEX €/m	500	3400

TRL: 8-9

Advantages:
High throughput capactiy
Low space demand
Low specific cost

Challenges:
High upfront cost
Re-assignment

Projects:
Leuna (DE)
Texas (US)

Gaseous H_2 Trailer

Property	Today[3]	Future[4]
Capacity kg_{H2}	400	1100
CAPEX €/kg_{H2}	500	600

TRL[3]: 9

Advantages:
No liquefaction required
Low investment cost
Established technology[3]

Challenges:
Low transport capacity

Projects:
London (UK)
Oslo (NOR)

Liquid H_2 Trailer

Property	Today	Future
Capacity kg_{H2}	4300	4300
CAPEX €/kg_{H2}	200	200

TRL: 9

Advantages:
Low investment cost
High transport capactiy
Established technology

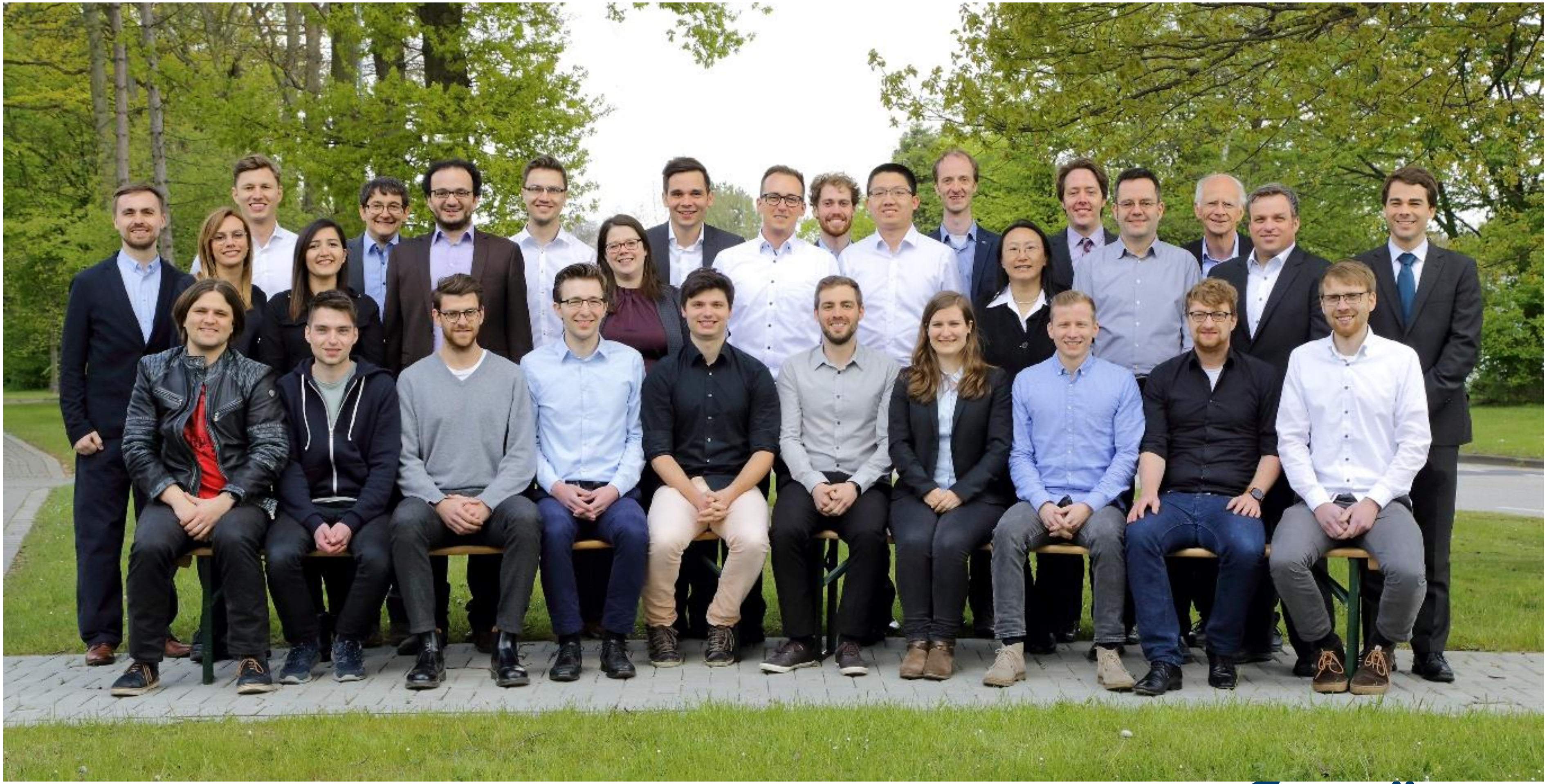
Challenges:
Requires liquefaction

Projects:
Vancouver (CAN)
London (UK)

TRL: Technology Readiness Level
CAPEX: Capital Expenditure

1: Pipeline diameter = 100 mm
2: Pipeline diameter = 1000 mm
3: Trailer pressure = 200 bar
4: Trailer pressure = 500 bar

Acknowlwdgement to the Systems Analysis Team, Marcelo Carmo, Meital Shviro and Marcus Stähler



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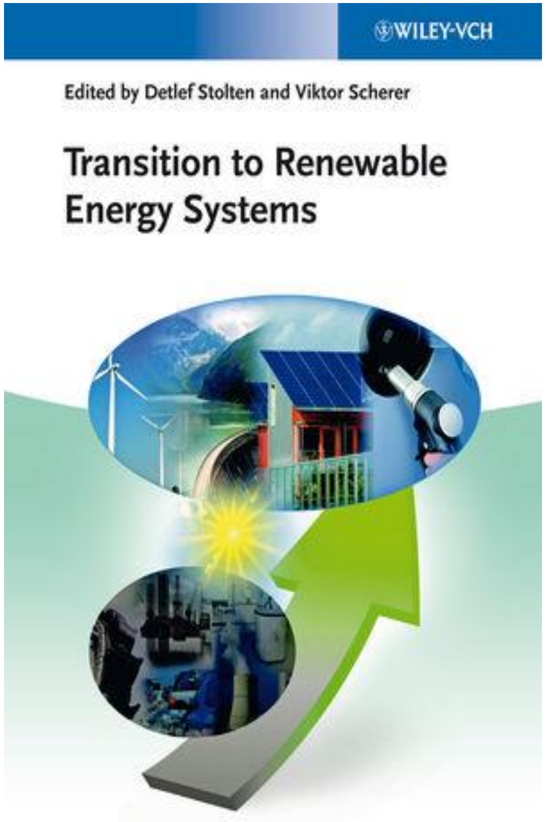

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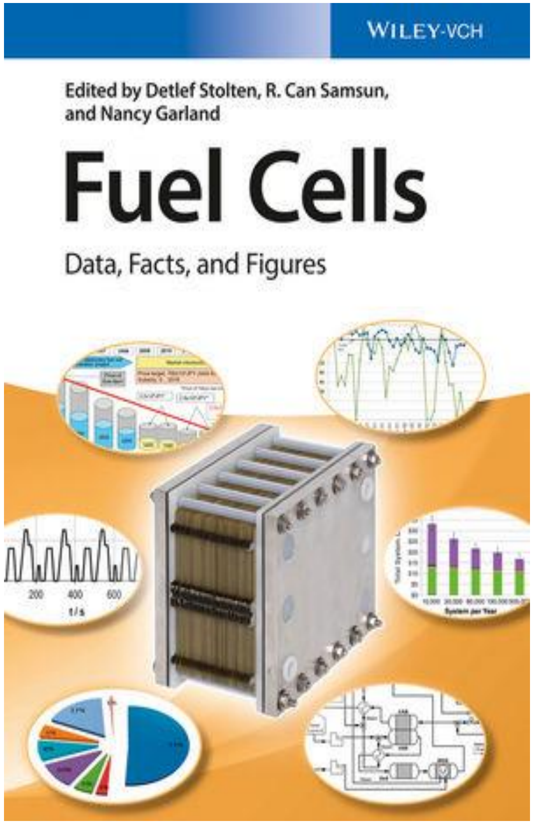
Transition to Renewable Energy Systems



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Fuel Cells

Data, Facts, and Figures