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PyFlex

HOCH SCHULE OFFEN BURG

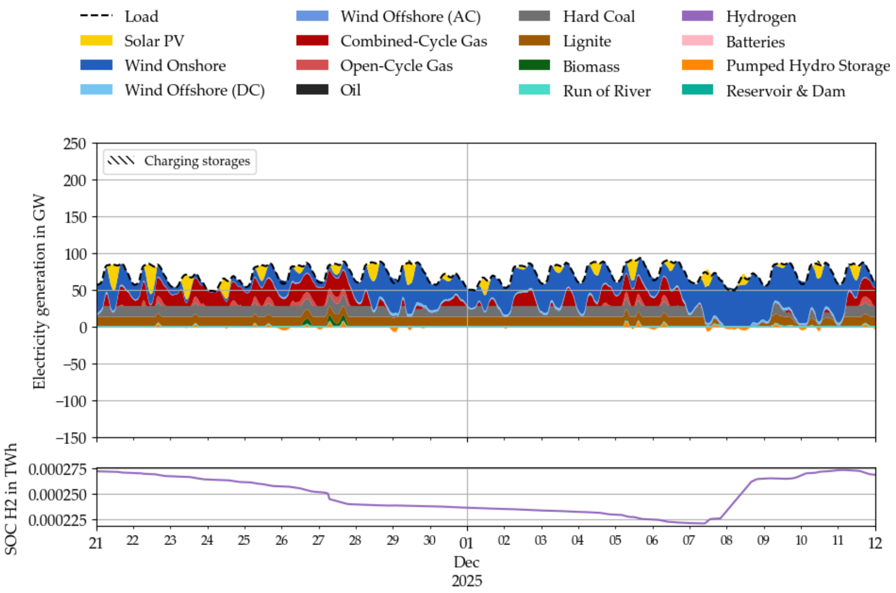
Dunkelflauten, Flexibilität und negative Emissionen: Systemwirkungen in einem wetterabhängigen Energiesystem

Anna Sandhaas, Niklas Hartmann | 13. Februar 2026

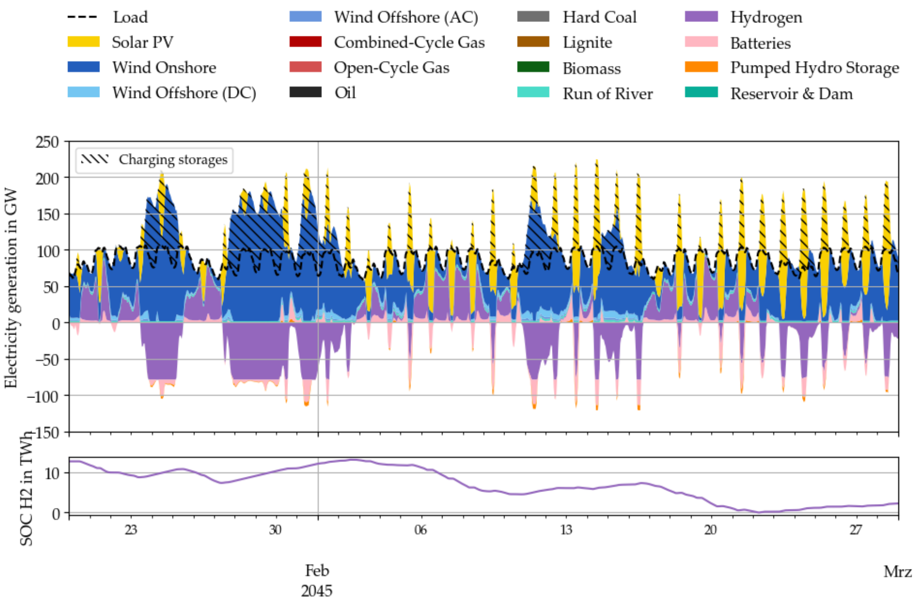
Ausgangssituation

- Unser zukünftiges Energiesystem ist wetterabhängig, das heißt wir brauchen Flexibilität

- Jahr 2025

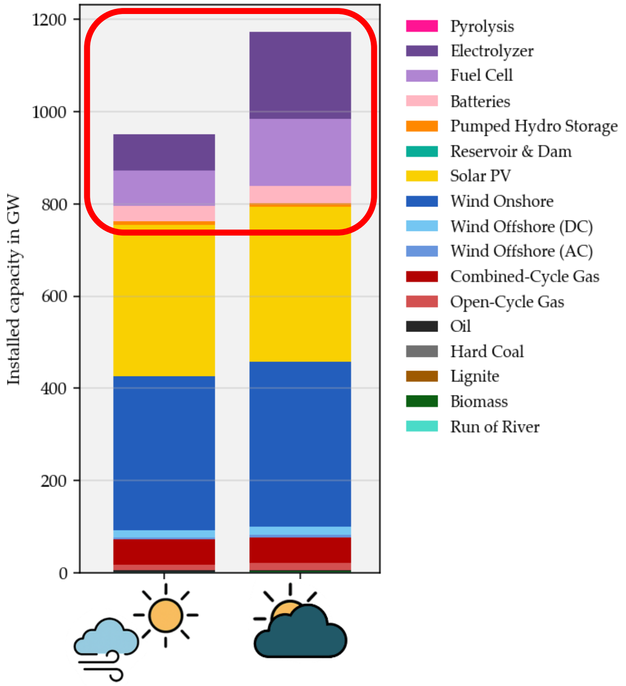


- Jahr 2045

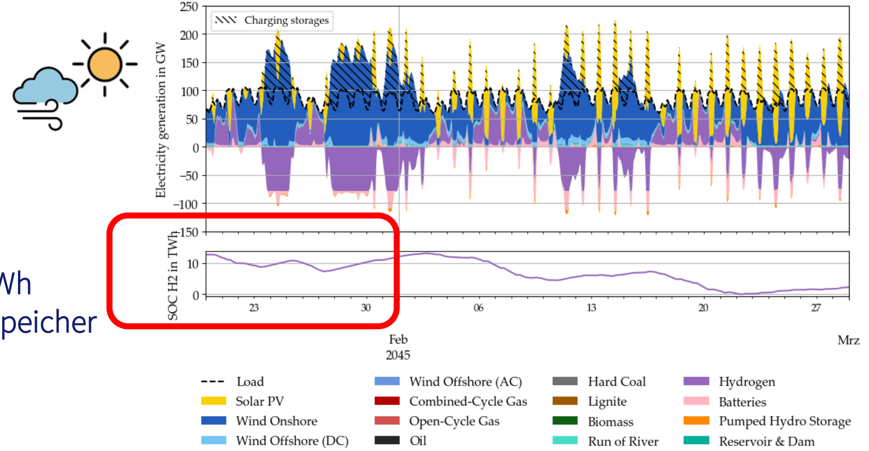


Dunkelflaute-Szenario und Klimaneutralität

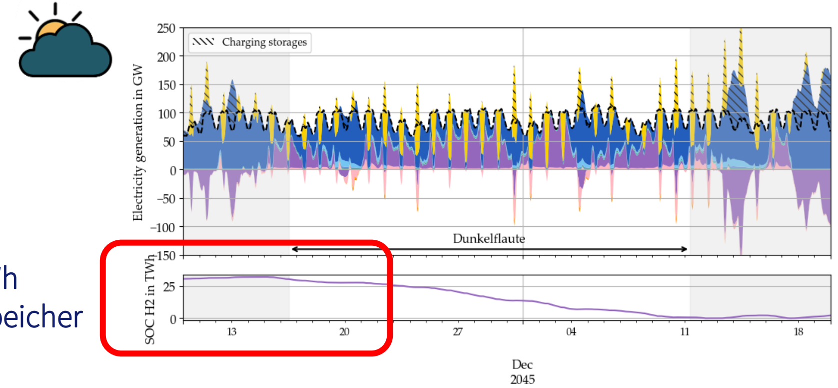
- Jahr 2045



13 TWh
H2-Speicher

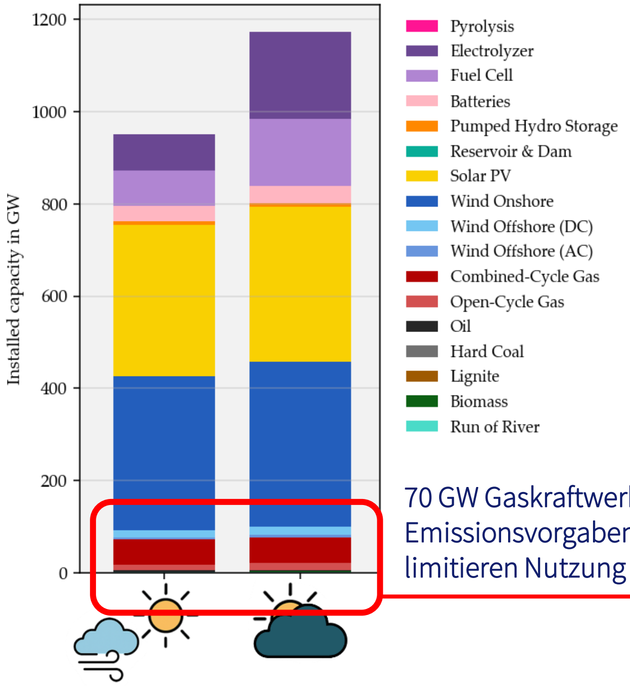


32 TWh
H2-Speicher

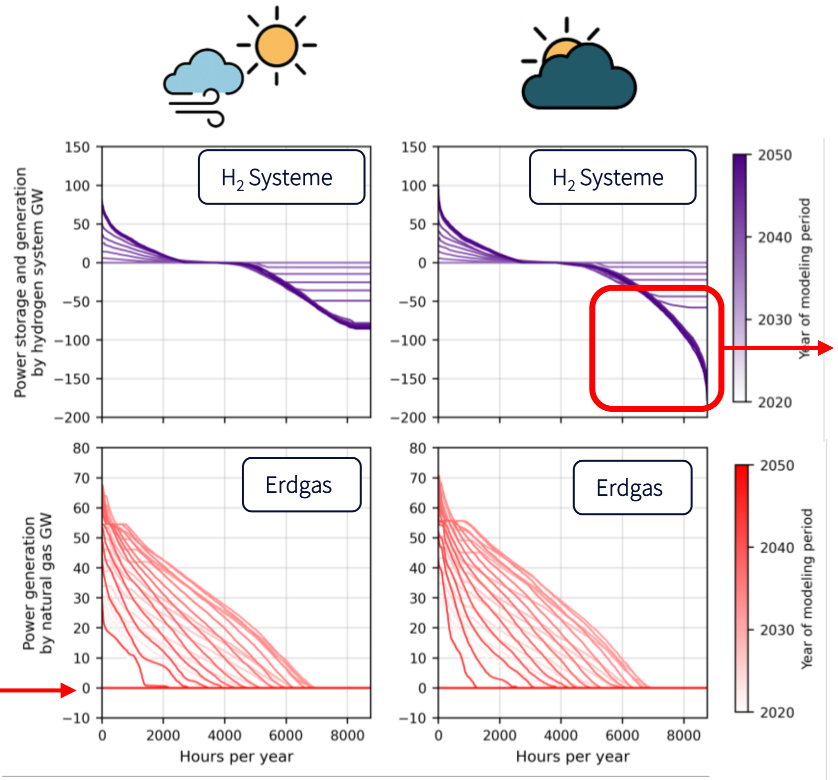


Dunkelflaute-Szenario und Klimaneutralität

Jahr 2045

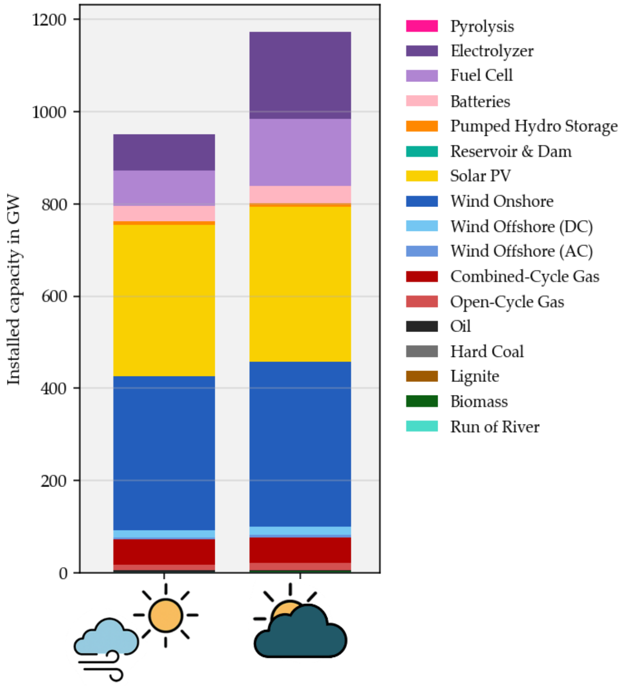


70 GW Gaskraftwerke, aber Emissionsvorgaben limitieren Nutzung ab 2045



Massive Überbauung der Speicher

Dunkelflaute-Szenario und Klimaneutralität



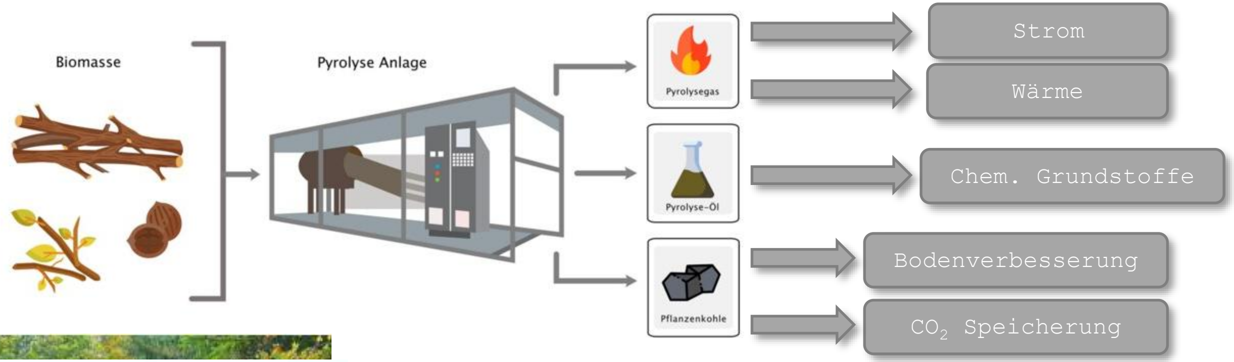
Wir brauchen ein heterogenes Flexibilitätsportfolio aus:

- Flexible Stromerzeugung durch Speicher
  - Jedoch: Wasserstoff wird massiv überbaut
- Flexible Stromerzeugung durch erneuerbare Energien
  - Aber: Das Potential von Biomasse und Wasserskraft ist begrenzt
- Flexible Stromerzeugung durch Erdgaskraftwerke limitiert aufgrund von Emissionsvorgaben
  - Weiterbetrieb möglich durch negative Emissionen

- Ist Pyrolyse die Antwort?

Die Pyrolyse

Biomasse	Pyrolyse Anlage	Produkte	Anwendung

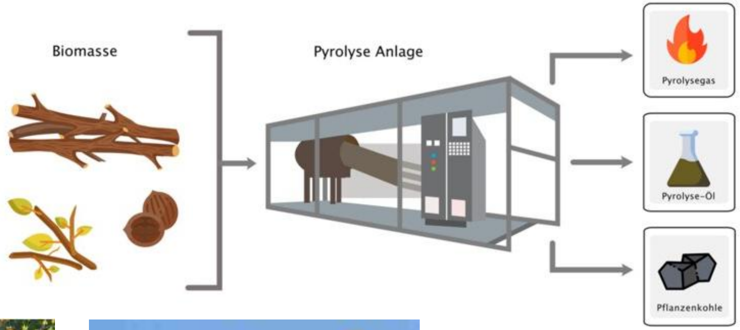


Quelle: www.sfv.de

Die Pyrolyse

Biomasse	Pyrolyse Anlage	Produkte	Anwendung

Total: 24.5 Mt/year



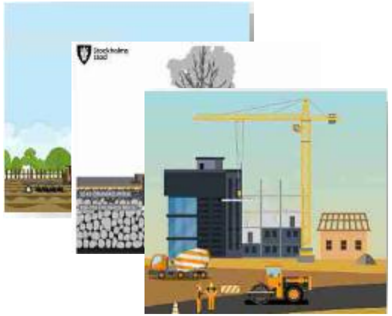
Strom

Total: 15.08 TWh/year

CO_2 Speicherung

Total: 12.63 Mt_{CO2}/year

Total: 6.13 $Mt_{biochar}$/year

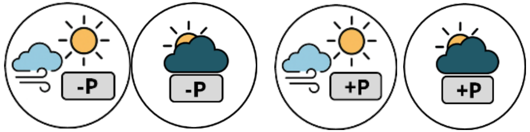


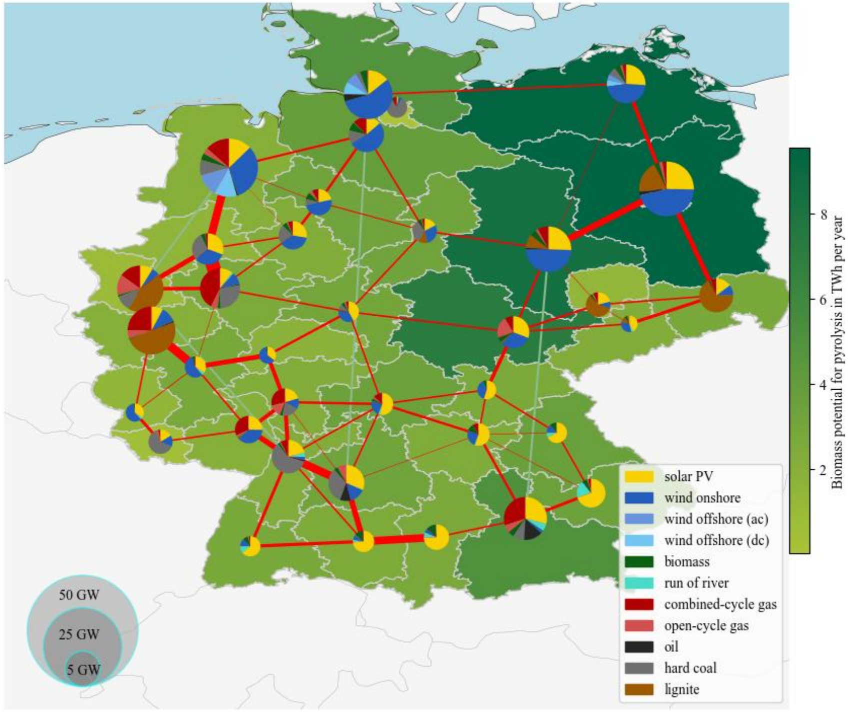
Quelle: www.sfv.de

Energiesystemmodell MyPyPSA

- Alle **bestehenden Kraftwerke** des Jahres 2020 werden im Modell erfasst
- Stundengenaue regionale **Stromnachfrage**
- Regionale stündliche **Wetterprofile**
- Jährliche Anpassungen **der techno-ökonomischen Parameter**
- …

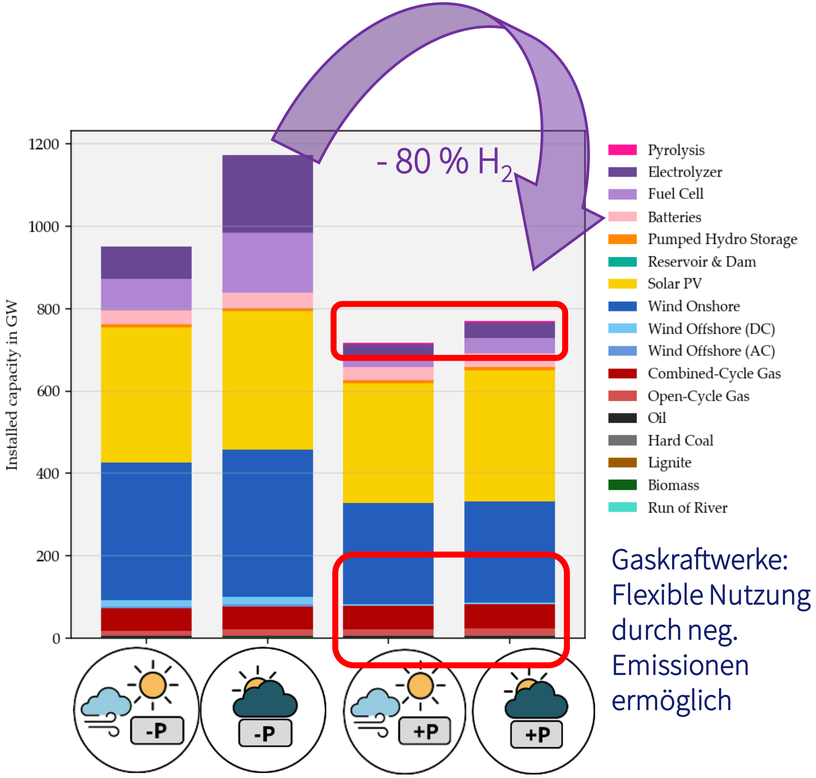
- Kostenminimale jährliche Optimierung bis 2050
- 4 Szenarien:
  - Sonne-Wind + Dunkelflaute
  - Je mit und ohne Pyrolyse



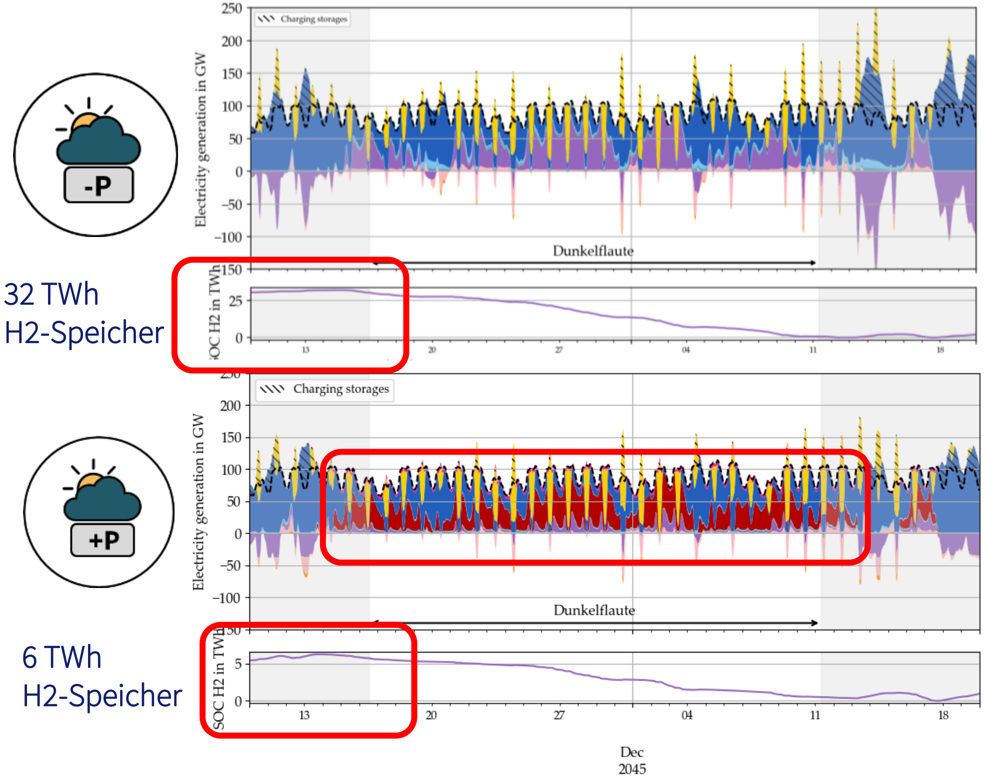


Quelle: Sandhaas und Hartmann, 2025

Dunkelflaute-Szenarien mit Pyrolyse

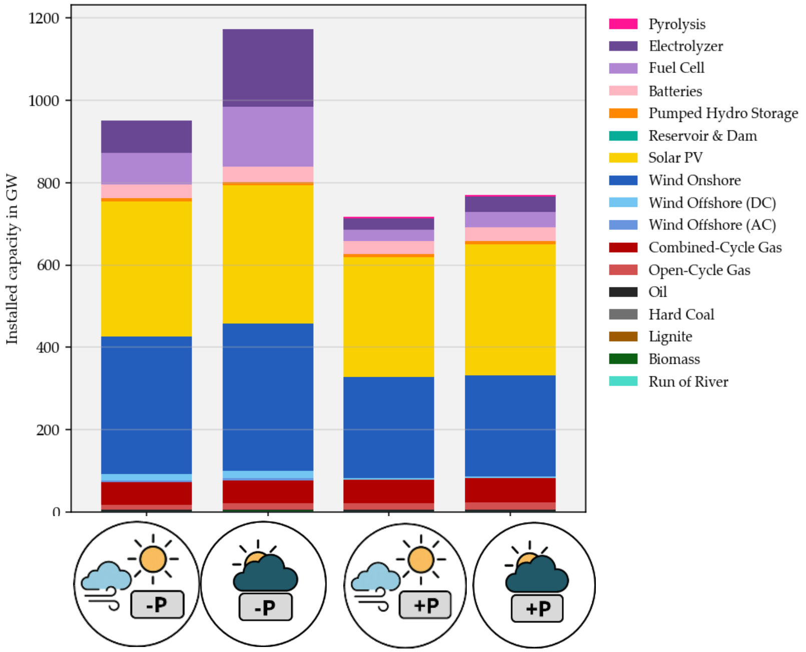


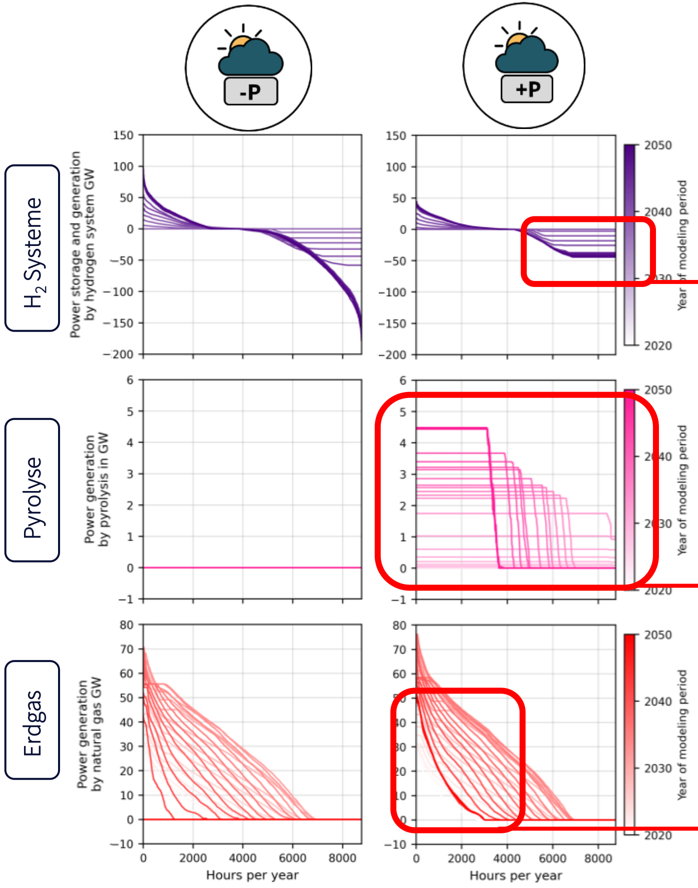
Gaskraftwerke: Flexible Nutzung durch neg. Emissionen ermöglicht



Quelle: Sandhaas und Hartmann, 2026

Jahresdauerlinien





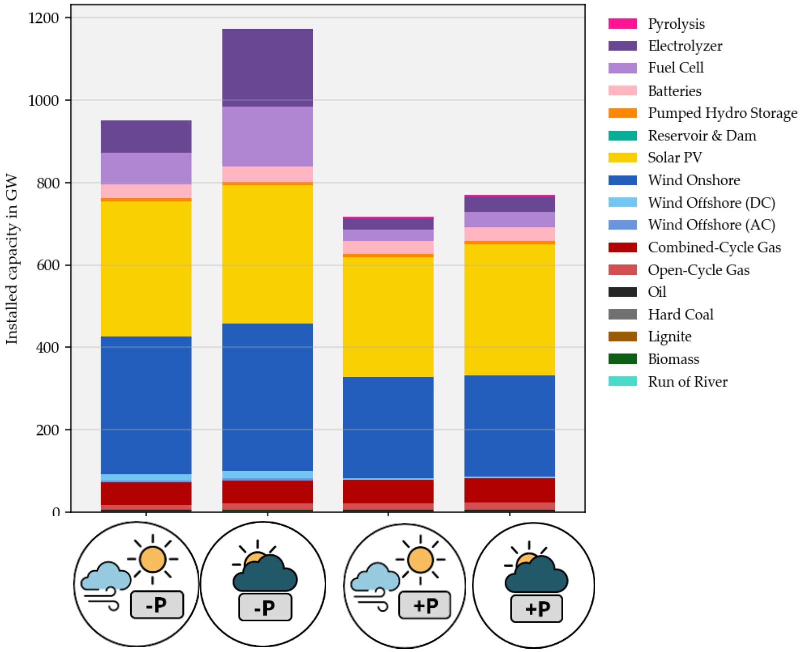
Häufigere Nutzung der H2-Systeme

Flexible Stromerzeugung aus Pyrolysegas

Erdgaskraftwerke als Reserve

Quelle: Sandhaas und Hartmann, 2026

Take aways



Quelle: Sandhaas und Hartmann, 2026

- **Dunkelflauten** bestimmen die Größe der Wasserstoffspeicher
- Pyrolyse senkt den **Wasserstoffspeicherbedarf** in Extremjahren um > 80 %
- **Negative Emissionen** aus Pflanzenkohle erlauben **zeitweisen Gaskraftwerkeinsatz**
- Pyrolyse erhöht die **Robustheit** klimaneutraler Stromsysteme

Take aways

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Energy system planning under variable solar and wind conditions: Pyrolysis as a key to system robustness through flexibility and negative emissions

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Negative emissions
System robustness

ABSTRACT

Interannual weather variability significantly influences the design and cost of climate-neutral electricity systems. Using forty historical weather years, this study quantifies how variations in solar and wind generation affect the optimal capacity mix, storage deployment, and total system costs for Germany's future net-zero system. Total annualized system costs range from 63 billion € to 86 billion €, while required hydrogen storage varies by more than a factor of three. The linear correlation analysis between weather characteristics and model outcomes shows that this variability is driven primarily by the duration of dunkelflauten (extended periods of simultaneously low wind and solar generation), which exhibits by far the strongest relationship with the total installed capacity of hydrogen storage systems. Each additional day of dunkelflaute increases hydrogen storage requirements by about 0.5 TWh. Integrating pyrolysis, which simultaneously provides dispatchable electricity and negative emissions from residual biomass, fundamentally changes this relationship. In myopic capacity expansion scenarios, pyrolysis reduces hydrogen storage requirements by more than 80 % in extreme weather years and enables temporary gas power operation without violating net-zero constraints. The findings highlight that pyrolysis can strengthen the robustness of renewable electricity systems by coupling flexibility provision with durable carbon removal, thereby mitigating uncertainty from future weather extremes.

1. Introduction

The transition to a climate-neutral electricity system represents one of the greatest challenges for energy policy and system planning [1]. As the share of variable renewable energy (VRE) sources such as wind and solar increases, their weather-dependent generation becomes a key determinant of system reliability [2], security of supply [3], and long-term investment planning [4,5]. Managing this variability therefore remains a central challenge in operating renewable-based power systems [6].

As electricity systems become increasingly weather-driven, not only average generation patterns but also interannual variability and extreme weather conditions become decisive for long-term system design. A particularly critical manifestation of such variability is the occurrence of a *dunkelflaute*, derived from the German *dunkel* (dark) and *flaute* (calm wind conditions), which denotes extended periods of simultaneously low wind and solar generation. Although no universally accepted definition exists [7–9], dunkelflauten are widely recognized as extreme stress tests for renewable-dominated power systems.

Recent events in Germany illustrate their relevance: pronounced dunkelflauten in November and December 2024 coincided with high demand, sharp price spikes, and near-full utilization of dispatchable thermal power plants [10]. Such events highlight the vulnerability of electricity systems during prolonged periods of low renewable generation and underscore the importance of sufficient system flexibility [11]. To ensure reliability in the coming decade, the German government has announced plans to build up to 12 GW of new gas-fired power capacity [12]. While these plants are intended to provide dispatchable flexibility and stabilize the system during periods of low renewable output, their operation conflicts with stringent emission reduction targets under the Climate Protection Act [13]. This tension motivates solutions that can provide flexibility without compromising decarbonization goals, either through emission-free flexibility options or through negative emissions that compensate residual fossil-based generation within net-zero constraints.

One promising candidate that combines both approaches is biomass pyrolysis. Pyrolysis is a thermochemical process in which residual biomass is converted under oxygen-limited conditions into energy carriers and biochar. From an electricity system perspective, the most relevant outputs are dispatchable electricity generation from pyrolysis gas and negative emissions associated with long-term carbon sequestration in biochar [14]. By coupling dispatchable power generation with durable carbon removal, pyrolysis offers a fundamentally different flexibility mechanism than storage-based approaches and may allow

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