



Integration

Renewable Energy Integration in the Energy System

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Recap



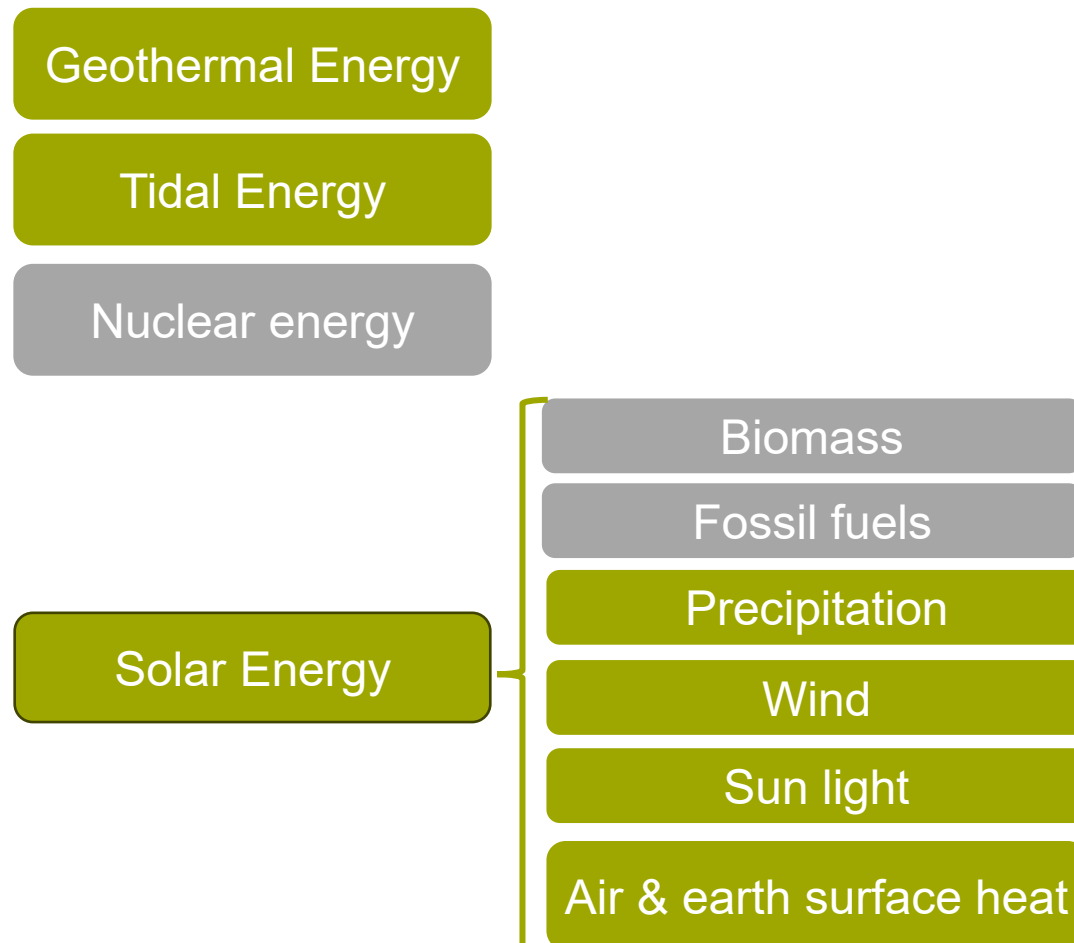
Energy transition

The main objective of the energy transition is to switch from the current fossil fuel-based energy system to a 100% renewable energy system.

- No golden solution. One source or one technology.
- Long gradual transition process.
- Changes on the energy system has consequences for the whole society.

Renewable energy

A **renewable energy source** is any energy source that replenishes itself **fast enough** to be considered inexhaustible on a human timescale.



PESTEL Analysis

A PESTEL analysis is a strategic framework used to evaluate the macro-environmental forces—Political, Economic, Social, Technological, Environmental, and Legal. When applied to the integration of renewable energy in the energy system, it helps policymakers and organizations map out the complex drivers and barriers that shape a sustainable, carbon-neutral future.



T1- Electric Grid Integration

Intermittency

- Solar and wind produce energy only when the sun shines or wind blows.
- Generation is variable and hard to predict with certainty.

Load Balancing

- Demand and supply must match in real time on the electrical grid.
- Imbalances cause frequency deviations, risking grid stability.

Peak Demand Mismatch

- Renewable peaks don't align with consumption peaks

Frequency Regulation

- Maintaining 50/60 Hz requires fast-responding reserves

Voltage Stability

- Distributed generation creates local voltage fluctuations

Grid Congestion

- Transmission lines weren't designed for bidirectional flows

T2 - Multi-Commodity Grid Approach

Electric Grid

- High voltage transmission lines
- Distribution networks (LV/MV)
- Must balance in real-time
- Backbone of the energy system

Heat Distribution Network

- District heating & cooling
- Industrial waste heat reuse
- Seasonal thermal energy storage
- Lower transport losses at large scale

Hydrogen Network

- Power-to-Gas: excess RE → H₂
- Repurposed natural gas pipelines
- Green hydrogen for industry & transport
- Seasonal and long-distance energy carrier

T3 – Integration of Energy Storage

**Minutes–
Hours**

Battery Storage

Short-term balancing

Connected at distribution level; responds in milliseconds; supports grid frequency and peak shaving

**Hours–
Days**

Pumped Hydro

Large-scale daily balancing

Utility-scale; connected to high-voltage transmission; store overnight excess, discharge during peak demand

**Days–
Months**

Hydrogen Storage

Seasonal & long-distance

Power-to-Gas plants convert surplus electricity; stored in tanks or gas grid; used in fuel cells or reconverted

**Hours–
Seasons**

Thermal Storage

Heat network buffer

Stores excess heat/cold in tanks or underground; directly coupled to district heating networks and industrial processes

T4 – Smart Grids and Digitalization

Bidirectional Energy Flows

Prosumers both consume and inject energy into the grid. Traditional one-way infrastructure must be upgraded to handle two-way flows of electricity, heat, and hydrogen.

Demand Response & Flexibility

Smart meters and IoT devices enable consumers to shift loads to match renewable availability. Industrial processes, EVs and heat pumps become active grid participants.

Sector Coupling via Digitalization

Digital platforms integrate electricity, heat and gas networks. AI and predictive algorithms optimize dispatch across all energy carriers simultaneously.

Data & Cybersecurity

Real-time data exchange requires robust communication protocols (e.g. IEC 61850). Increased connectivity also creates new cybersecurity vulnerabilities.

Economic Factors

Levelized Cost of Energy (LCOE)

Solar and onshore wind are now the cheapest sources of new electricity generation in most markets. LCOE for renewables has fallen 80–90% over the past decade, making them cost-competitive with fossil fuels.

Investment Trends

Global renewable energy investment exceeded €500 billion per year in recent years. However, grid infrastructure and storage require additional trillions of dollars of investment by 2050.

Job Creation

The renewable energy sector employs over 13 million people globally (IEA, 2023). The transition creates new jobs but also requires reskilling workers from fossil fuel industries.

Energy Price Stability

Renewables offer stable long-run marginal costs (near zero fuel cost). However, upfront capital is high and wholesale electricity prices become more volatile with high variable RE shares.

Political Factors

EU Green Deal & Paris Agreement

The EU aims for climate neutrality by 2050 and 55% emission reduction by 2030. National governments must translate these targets into binding energy and infrastructure plans.

Subsidies & Incentive Schemes

Feed-in tariffs, contracts for difference (CfD) and renewable portfolio standards have been key policy tools. Many are shifting toward market-based mechanisms as costs fall.

Energy Independence & Security

The 2022 energy crisis accelerated European RE expansion. Reducing dependence on fossil fuel imports is now a core political driver alongside climate goals.

International Cooperation

Cross-border grid interconnection (e.g. European IEM) requires political agreements. Energy diplomacy is increasingly important for hydrogen trade and offshore wind.

Legal Factors

Permitting & Planning Frameworks

Slow and complex permitting processes are one of the biggest barriers to renewable deployment in Europe. Streamlining is a key priority of the EU's REPowerEU plan.

Grid Access & Connection Rights

Third-party access (TPA) rules require grid operators to provide non-discriminatory access. Regulations define connection costs and priority dispatch rules for renewables.

International Energy Trade Law

Cross-border electricity and hydrogen trade requires harmonized legal frameworks. Bilateral and multilateral agreements govern interconnector use and balancing responsibilities.

Liability, Insurance & Standards

As grids become more complex, liability frameworks for outages, data breaches and infrastructure failure need to evolve. Technical standards (IEC, IEEE) have legal standing.

Social Factors

Public Acceptance & NIMBY

While renewables enjoy broad public support, local opposition to wind farms, solar parks and grid infrastructure remains common. Perceived impacts on landscape, noise and property values drive resistance.

Energy Equity & Access

The energy transition must ensure fair distribution of costs and benefits. Low-income households face disproportionate energy poverty risks if transition costs are poorly distributed.

Consumer Behavior & Awareness

Prosumerism, energy communities and demand flexibility require active consumer participation. Digital tools and education are key to unlocking behavioral change.

Community Energy Projects

Cooperatives and local energy communities allow citizens to invest in and benefit from local renewable projects. These models increase social acceptance and distribute value locally.

Environmental Factors

Carbon Emission Reductions

Replacing fossil fuels with renewables is the single biggest lever for decarbonizing the energy system. Wind and solar have lifecycle emissions 10–50x lower than natural gas per kWh.

Land Use & Biodiversity Impact

Large solar farms and wind installations require significant land areas. Site selection must carefully consider ecological sensitivity, habitat disruption and visual landscape impacts

Life Cycle Analysis (LCA)

Manufacturing solar panels, wind turbines and batteries consumes energy and materials. Full LCA shows renewables are net positive in 1–4 years, but material supply chains need scrutiny.

Circular Economy Challenges

End-of-life solar panels, wind turbine blades and batteries create new waste streams. Recycling infrastructure and design-for-disassembly approaches are urgently needed.

Content references

[IEA – World Energy Outlook 2023](#)

[IRENA – World Energy Transitions Outlook 2023](#)

[European Commission – REPowerEU Plan](#)

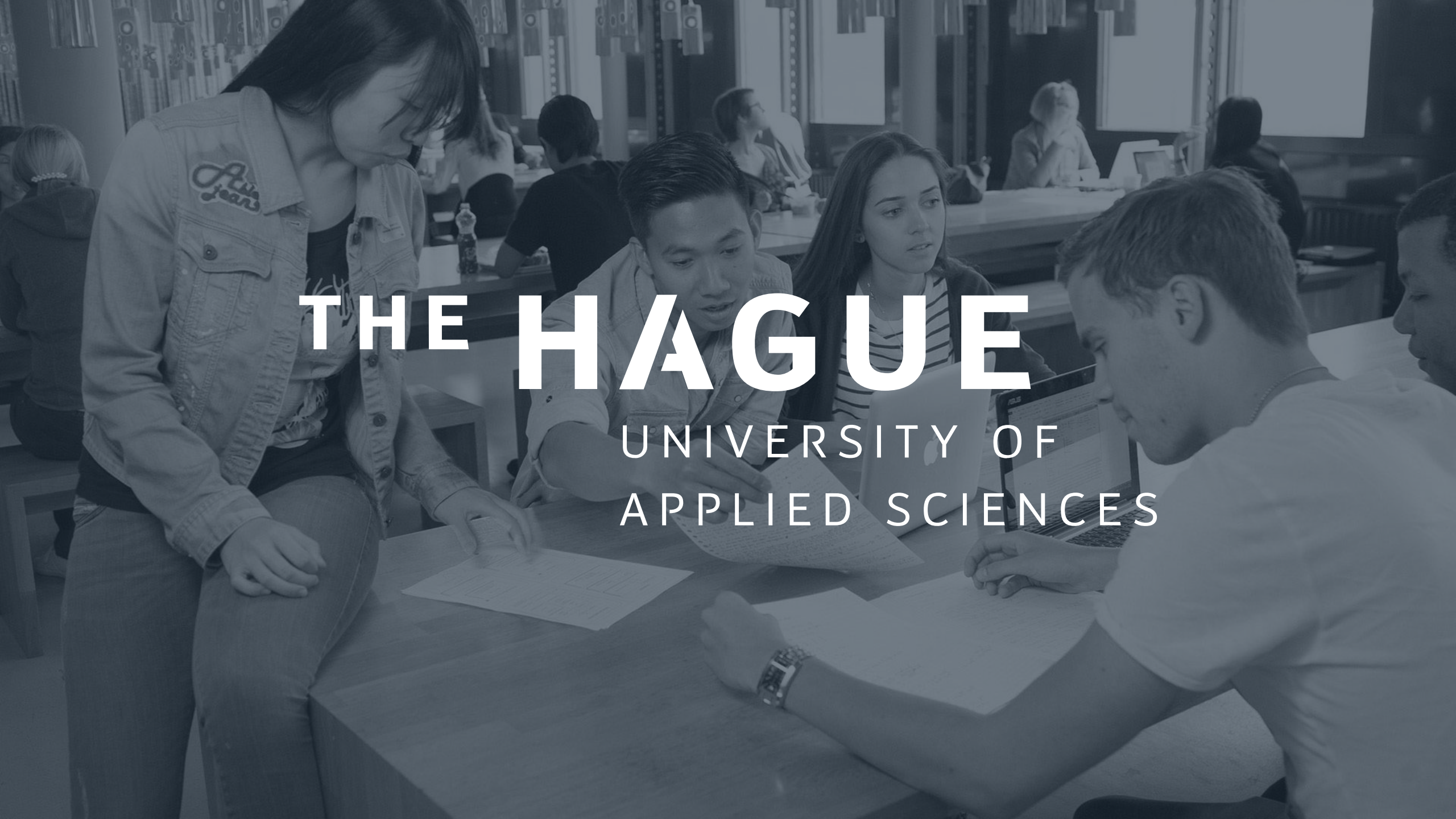
[IPCC – AR6 Climate Change 2022: Mitigation](#)

[IEA – Electricity Grids and Secure Energy Transitions \(2023\)](#)

[ENTSO-E – Ten-Year Network Development Plan \(TYNDP\)](#)

[IRENA – Innovation Landscape for Smart Electrification](#)

[EU – Renewable Energy Directive \(RED III\), 2023](#)

A grayscale photograph of a modern classroom or study hall. In the foreground, a group of four students are gathered around a table. A young woman on the left, wearing a denim jacket with a 'Live Years' patch, is leaning over and pointing at a document. A young man next to her is also looking at the document. Behind them, another young woman is looking on. To the right, a young man is sitting at the table, looking at a laptop. In the background, other students are seated at long tables, and the room has large windows and decorative elements hanging from the ceiling.

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