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IPESE
Industrial Process
and Energy Systems
Engineering

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School of Engineering

CIRAIG

ENV-421
Energy Technologies

Jonas SCHNDIRIG

Week 9

École
polytechnique
fédérale
de Lausanne

This week
Agenda

	Week 2	Week 4	Week 7	Week 9
Lectures	Energy System Fundamentals	Energy Conversion Technologies	Technologies' Impacts	Climate Impact on Energies
Applications & Excercises	The Swiss Energy System Evolution & Perspectives	Efficiencies & Classification	Conference *Is it all about renewable energies?* Closing the Balance & Defining Compromises	*Powerplay Game*

Project: Addressing Contemporary Challenges to the Swiss system
Energy-independent and carbon-neutral Switzerland 2050

AGENDA

Recap of Previous Lectures

Climate Change Impacts on RES

Feedback Effects (RES on Climate)

Adaptation Strategies

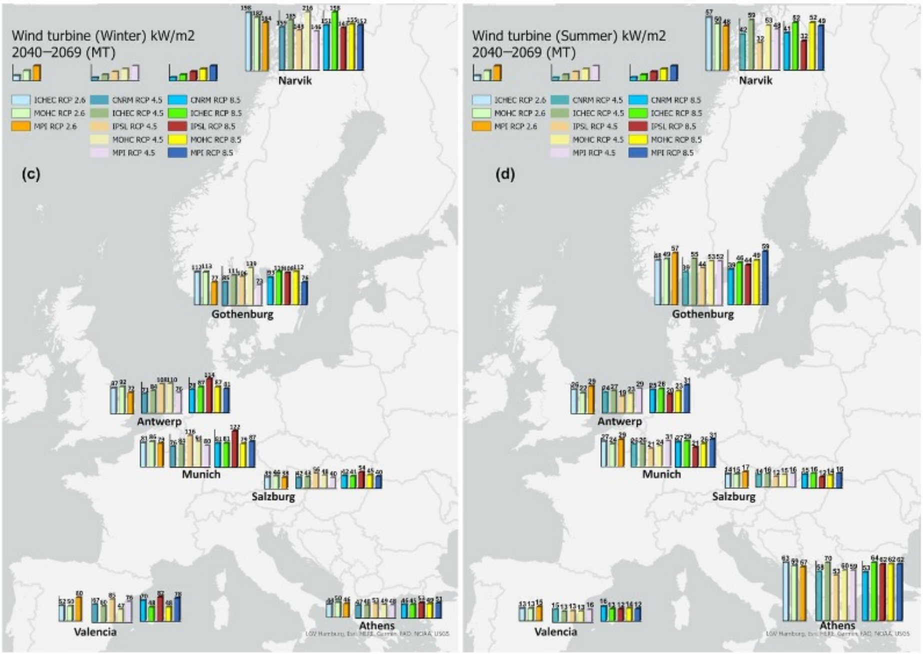
Emerging Methodologies

Global Context & Swiss Case Study

Introduction: Why Climate Adaptation Matters

- IPCC AR6 highlights:
  - 1.5–2.0°C warming alters wind & precipitation patterns in key regions
- Economic Risks:
  - Potential O&M cost increases of ~10–25% for some renewables under extreme conditions
  - Up to 0.2–1.0% of global GDP at risk from energy supply disruptions (Wasti et al., 2022)
- Objective:
  - Integrate climate variables into renewable energy planning & design

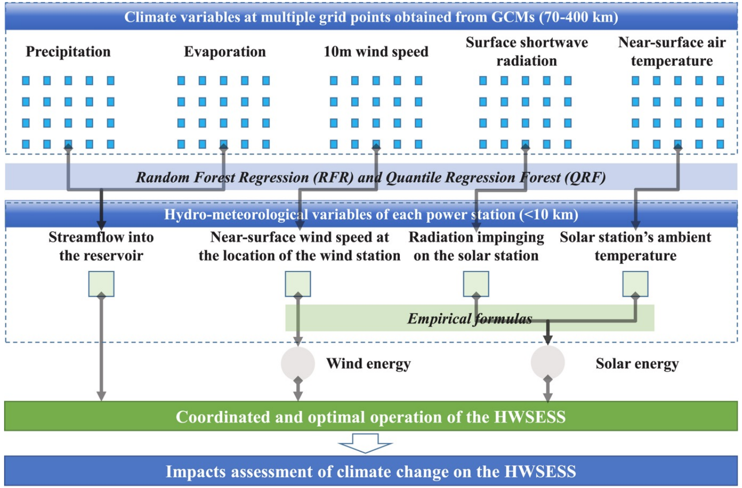
Wind Energy Impacts (Global Overview)



Results for 2040–2069 as medium term (MT) out of 13 climate scenarios: (c) winter wind turbine output, (d) summer wind turbine output.
Climate Change and Renewable Energy Generation in Europe—Long-Term Impact Assessment on Solar and Wind Energy Using High-Resolution Future Climate Data and Considering Climate Uncertainties, Yang et al. 2022

- Installed Capacity:
  - 539 GW (2017) → ~837 GW by 2021 (GWEC, 2022)
  - Could reach ~36% global electricity by 2050 *(Solaun & Cerdà, 2019)*
- Climate Change Threats:
  - Shifts in average wind speed (±10% regionally)
  - Air density drops with temperature increase (~1% efficiency loss per 2°C)
  - Extreme storms affecting turbine integrity
- Regional Differences:
  - Northern Europe: Potential +10% in wind speed
  - Southern Europe: −5% to −15% *(Yang et al., 2022)*

Wind Energy Methodological Details

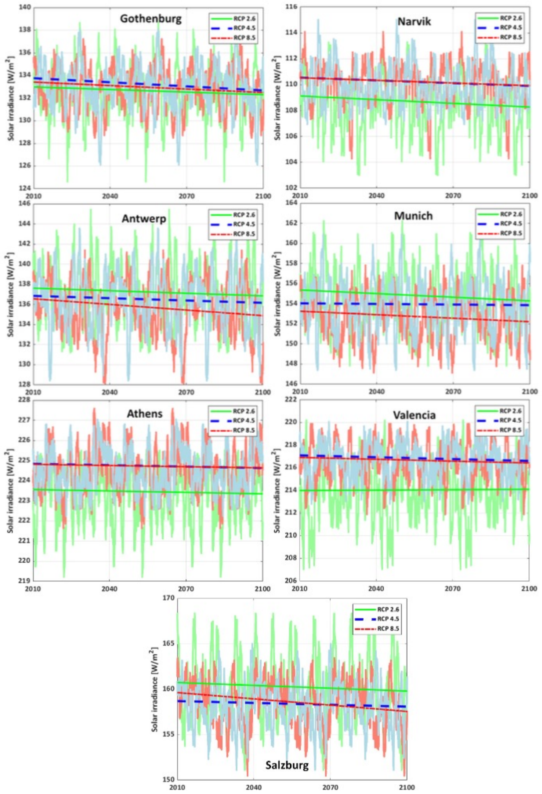


General form of the EIA model for investigating the impacts of climate change on the HWSESS considering each individual power station.
Assessment of climate change impacts on the hydro-wind-solar energy supply system, Zhang et al. 2022

- Modeling Approaches:
  - GCM–RCM downscaling (HadGEM2-ES, IPSL-CM5A, MPI-ESM-LR) under RCP 4.5 & 8.5 (Russo et al., 2022)
  - Turbine power curves: capturing cut-in, rated, and cut-out wind speeds
- Seasonal Variability:
  - Winter generation often ~50% higher than summer in high-latitude regions
  - Summer lull of −20–30% in output
- Uncertainty Analysis:
  - Ensemble averaging across multiple climate models to capture ±10–25% range in wind projections

Solar Energy Impacts (Global Overview)

Jonas Schnidrig



- Global Capacity:
  - ~707 GW by 2020 (IEA, 2021)
  - Potential for 22–25% of global electricity by 2050 (Solaun & Cerdà, 2019)
- Climate-Driven Efficiency Changes:
  - ~−0.5% panel efficiency per +1°C
  - Dust & aerosol deposition can reduce output 2–6% regionally
- Regional Variations (Gernaat et al., 2021):
  - Southern Europe: Up to +5%
  - Northern Europe: ~−5% to 0%
  - Tropical regions: Slight declines due to high temperature

Solar irradiance trend regression analysis for RCP 2.6 (green), RCP 4.5 (blue), and RCP 8.5 (red) in seven cities during the period of 2010–2100, which is a combination of 5 GCMs.
Climate Change and Renewable Energy Generation in Europe—Long-Term Impact Assessment on Solar and Wind Energy Using High-Resolution Future Climate Data and Considering Climate Uncertainties, Yang et al. 2022

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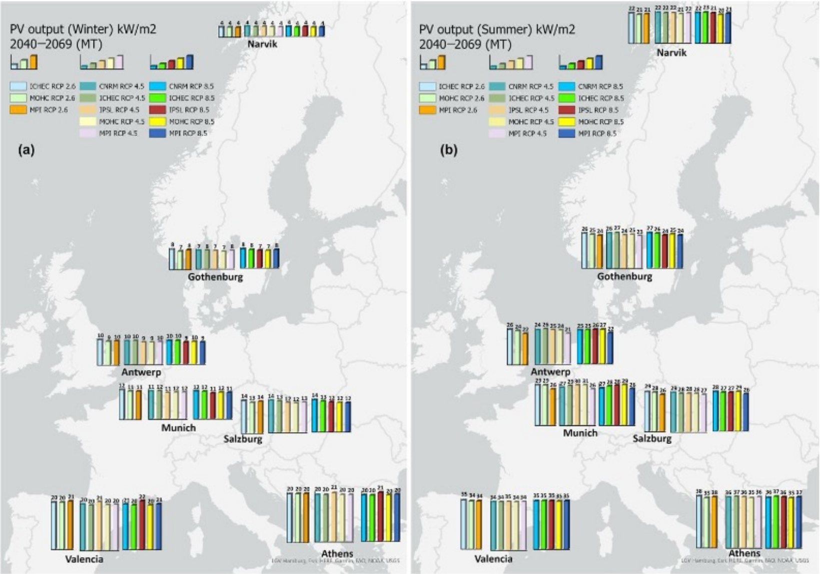
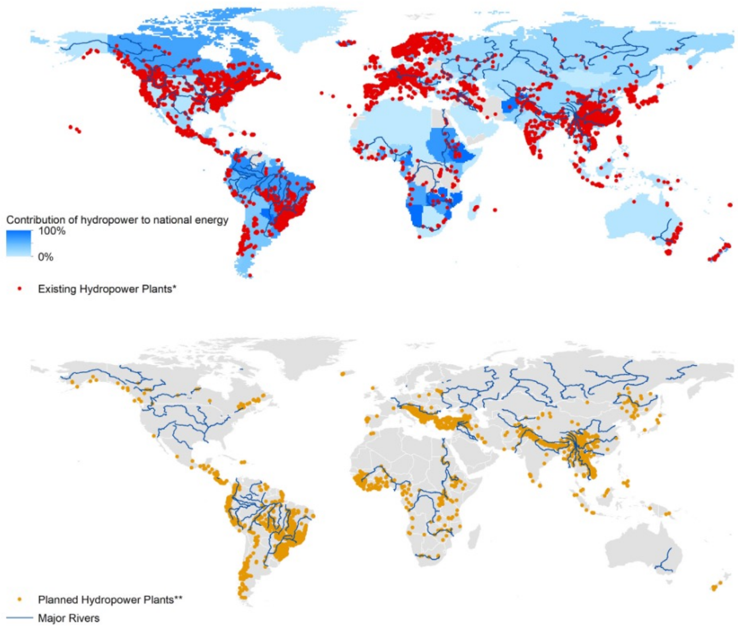
Solar Energy: Methodological Details



Results for 2040–2069 as medium term (MT) out of 13 climate scenarios: (a) winter PV turbine output, (b) summer PV turbine output.
Climate Change and Renewable Energy Generation in Europe—Long-Term Impact Assessment on Solar and Wind Energy Using High-Resolution Future Climate Data and Considering Climate Uncertainties, Yang et al. 2022

- Climate Data & Scenarios:
  - RCA4 downscaling of multiple GCMs, focusing on 2010–2099
  - Time slices:
    - near-term (2010–2039)
    - mid-term (2040–2069)
    - long-term (2070–2099)
- Metrics:
  - Hourly irradiance, temperature, and cloud cover
  - Panel efficiency modeled using temperature coefficients (−0.4% to −0.5%/°C)
- Seasonal Patterns:
  - Northern Europe:
    Summer output 2–3× winter levels
  - Subtropical regions:
    Dust storms reduce output by ~5–10% in extreme cases

Hydropower: Current Status



Contribution of hydropower to the national energy mix (World Bank (2015), updated with data from IHA (2020b) for Asia and Latin America. Locations of existing hydropower plants are shown as red dots (Global Energy Observatory, 2018). Locations of hydropower plants planned for completion by 2030 are shown as orange dots (Zarfl et al., 2015)

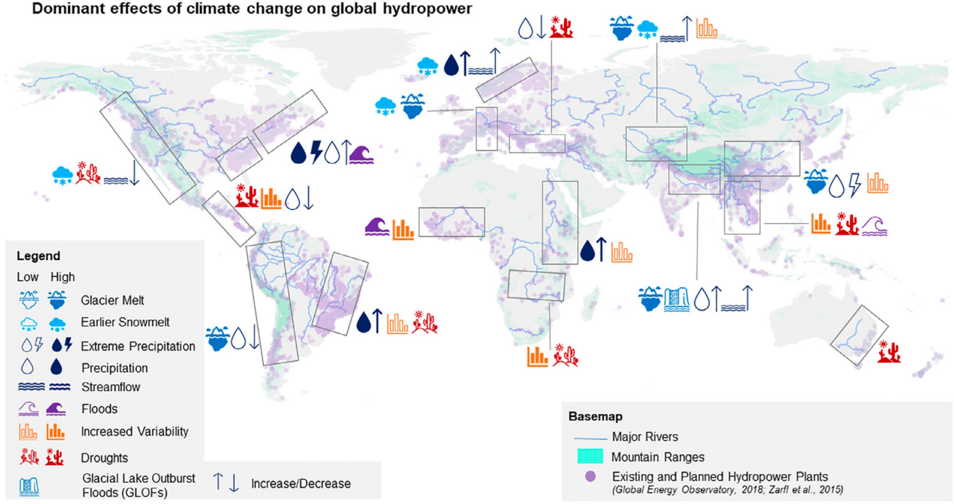
Climate change and the hydropower sector: A global review, Wasti et al. 2022

- Global Capacity:
  - >1,360 GW by 2021 (IHA, 2022)
  - Major countries: China ~340 GW, Brazil ~109 GW, US ~102 GW
- Cost Trends:
  - LCOE rose from ~$0.04/kWh in 2010 to ~$0.05/kWh in 2017 (Solaun & Cerdà, 2019)
- Significance:
  - Hydropower supplies ~16% of global electricity
  - Multipurpose benefits: irrigation, flood control, energy storage

Hydropower: Climate Vulnerabilities

Jonas Schnidrig

Dominant effects of climate change on global hydropower



The effect of climate change on global hydropower generation, based on observed trends and near-future projections. The effects are indicated by two levels of symbols: high and low. Generally, if a climate change effect is discussed in more than 50% of the review papers for the region, a "high" symbol (filled in) is adopted. Also shown are the major rivers (blue lines), mountain ranges (cyan hue), and the location of existing and planned hydropower plants (purple dots) (Global Energy Observatory, 2018; Zarfl et al., 2015)
Climate change and the hydropower sector: A global review, Wasti et al. 2022

- Shifts in Hydrological Patterns:
  - Possible ±30–40% streamflow changes in glacier-fed or monsoon-affected regions (Wasti et al., 2022)
- Glacier Melt Dynamics:
  - Himalayas: +10–20% in meltwater until ~2050, decline afterward
  - European Alps: earlier snowmelt shifting peak flow from summer to spring
- Extreme Events:
  - Floods threatening dam safety
  - Droughts causing reservoir drawdown, impacting generation

Hydropower: Methodological Approaches

EPFL longread "Energies Go Green"
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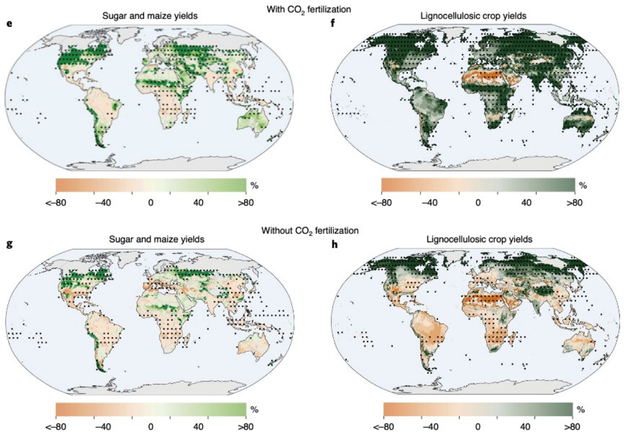
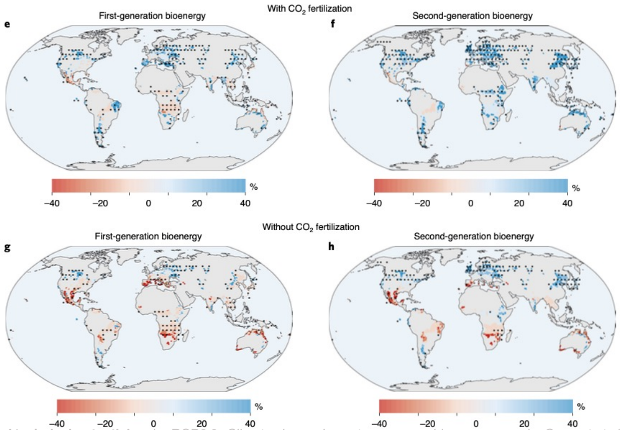
- Key Models:
  - Semi-systematic review of post-2010 studies (Wasti et al., 2022).
  - Integration of GCM precipitation data with flow-runoff models.
- Additional Factors:
  - Glacier Lake Outburst Flood risks in high-mountain regions.
  - Sedimentation and reservoir management over long lifespans.
- Case Analyses:
  - Transboundary water contexts, e.g., Indus, Nile.

Biomass & Other Renewables



Multi-model mean change in **climate patterns and yields** determining renewable energy potential for RCP6.0.
Climate change impacts on renewable energy supply, Gernaat et al. 2021



Multi-model mean change of **technical potential** under RCP6.0. *Climate change impacts on renewable energy supply, Gernaat et al. 2021*

- Biomass:
  - Affected by crop yields, biodiversity shifts, water availability.
  - Potential ±20% variation in yields under different RCP scenarios.
  - CO_2 fertilization can boost productivity in some temperate zones (Gernaat et al., 2021).
- Wave & Geothermal:
  - Wave power dependent on wind pattern changes; few conclusive projections.
  - Geothermal less sensitive to surface climate but can face water constraints.

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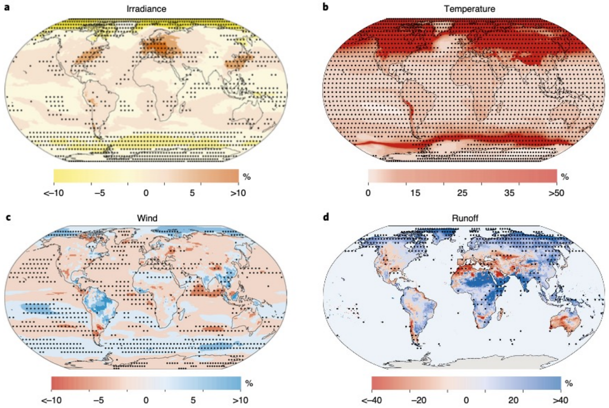
Quantifying Overall Impacts: Comparative Insight



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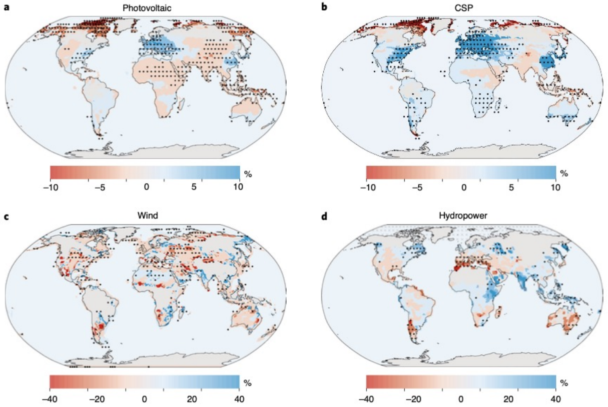
Climate change impacts on renewable energy supply, Gernaat et al. 2021

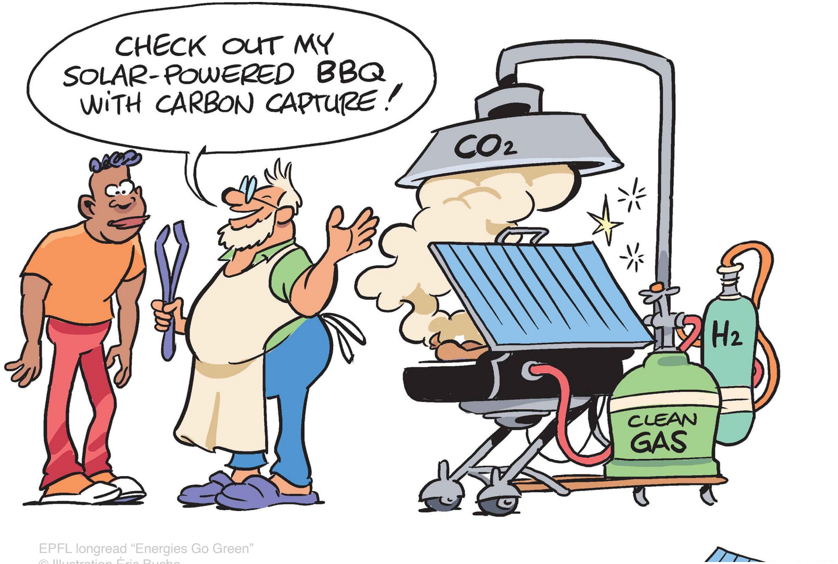


Multi-model mean change of **technical potential** under RCP6.0. *Climate change impacts on renewable energy supply, Gernaat et al. 2021*

- Integrated Assessment Models: IMAGE, REMix, or EnergyScope.
- Typical Ranges of Change (Gernaat et al., 2021; Solaun & Cerdà, 2019):
  - Solar: ±5% globally, localized up to ±10%.
  - Wind: ±10–20% regionally, extremes up to ±45% for offshore.
  - Hydropower: ±30–40% in regions with strong dependence on glacial or monsoon regimes.
- Economic Implications:
  - GDP impacts relatively small (<1% on national scales) but can accumulate in vulnerable areas.

AGENDA

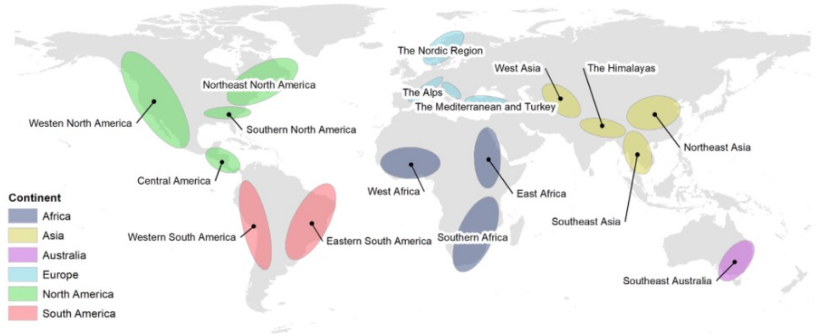
GHG Emissions Reduction & Climate Mitigation



EPFL longread "Energies Go Green"

- Potential: Renewables could decarbonize ~90% of global electricity by 2050 (Osman et al., 2023).
- Impact:
  - Lower CO_2, CH_4, NO_x emissions.
  - Reduced air pollution, improved public health.
- Global Warming Limit:
  - Renewables key to 1.5–2°C targets per IPCC.

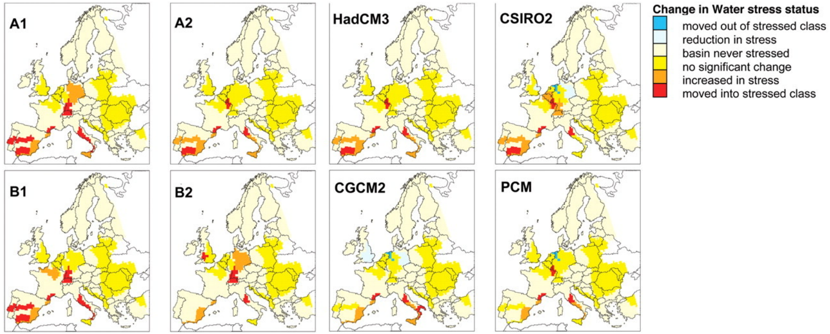
Land-Use and Microclimate Effects



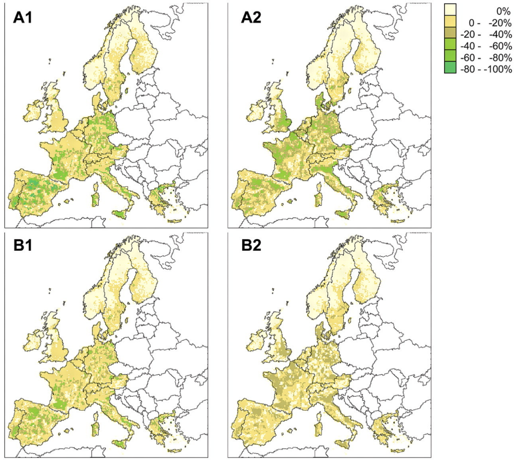
Regions of the world as relevant to the discussion of risks to hydropower from climate change
Climate change and the hydropower sector: A global review, Wasti et al. 2022

- Large-Scale Deployment Issues:
  - Solar farms altering albedo, leading to local heating/cooling.
  - Wind farms modifying local boundary-layer dynamics.
- Hydropower:
  - Potential for reservoir-induced microclimates.
  - Reservoir GHG emissions (methane) from submerged biomass.

Aquatic and Ecosystem Considerations



Stress status of water basins by 2080 considering climate change and population growth, compared with the hypothetical case of no climate change. Stressed water basins have less than 1700 m³ capita⁻¹ year⁻¹.
Ecosystem Service Supply and Vulnerability to Global Change in Europe, Schröter et al. 2005



Change in cropland area (for food production) by 2080 compared with the baseline (percentage of EU15+ area) for the four storylines [A1FI (A1), A2, B1, and B2] with climate calculated by HadCM3.
Ecosystem Service Supply and Vulnerability to Global Change in Europe, Schröter et al. 2005

- Hydropower:
  - Dam operations alter riverine ecosystems (fish migration, sediment transport).
  - Potential synergy with "*floating*" solar to reduce evaporation.
- Biomass:
  - Land-use competition with food and biodiversity.
  - Soil carbon depletion or enrichment depending on management.

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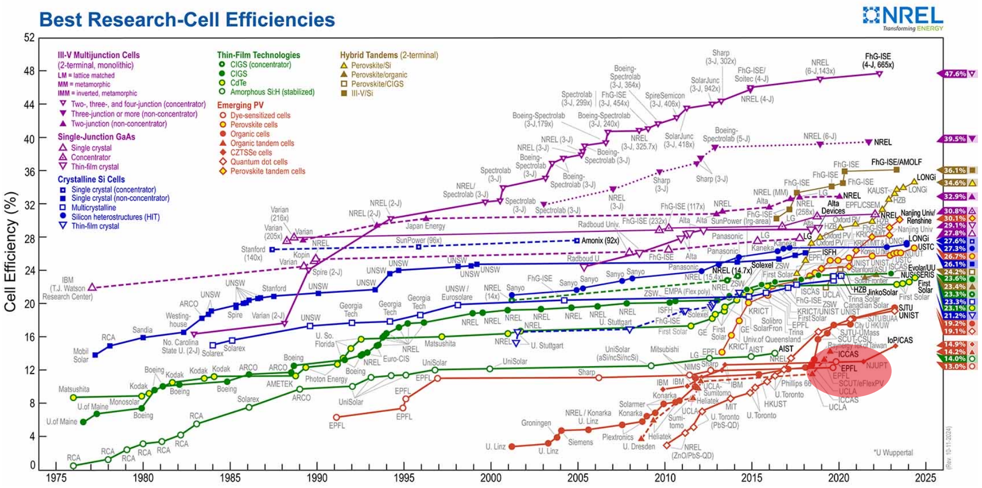
Infrastructure & Design Innovations



Best Research-Cell Efficiency Chart
NREL maintains a chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present.
©NREL 2025

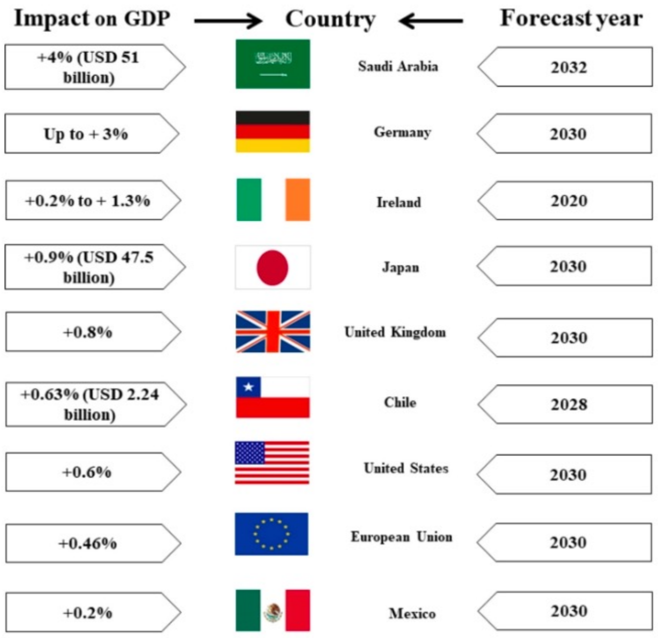
- Improved Turbine Materials:
  - Higher wind-speed tolerances, storm-resilient designs.
  - Reinforced blade structures for offshore sites.
- Solar Panel Adaptations:
  - Heat-resistant coatings, cleaning systems for dust-prone areas.
  - Bifacial PV increasing efficiency in diffuse light conditions.

Flexible & Hybrid Energy Systems

Hybrid system Wind – Hydro-Dam Furkapass

- Concept: Combining multiple renewables (solar–wind–hydro–storage) to balance variability.
- Evidence:
  - Hybrid systems reduce LCOE and smooth output variability by ~15–25% (Osman et al., 2023).
  - Seasonal complementarity (e.g., solar in summer, wind in winter).
- Practical Examples:
  - Solar–Wind farms with battery or pumped-hydro storage in Europe.

Policy and Economic Instruments



Renewable energy from an economic point of view. The figure analyzes the impact of renewable energy use from an economic aspect. GDP refers to gross domestic product, and USD refers to the United States dollar. Data from IRENAc
Cost, environmental impact, and resilience of renewable energy under a changing climate: a review, Osman et al. 2022

- Key Measures:
  - Carbon pricing to internalize externalities.
  - Feed-in tariffs or auction schemes for renewable deployment.
  - Incentives for climate-resilient infrastructure in vulnerable regions.
- Investment Needs:
  - Wind alone might require ~$5 trillion by 2050 (Solaun & Cerdà, 2019).
  - Public–private partnerships to de-risk capital in emerging markets.

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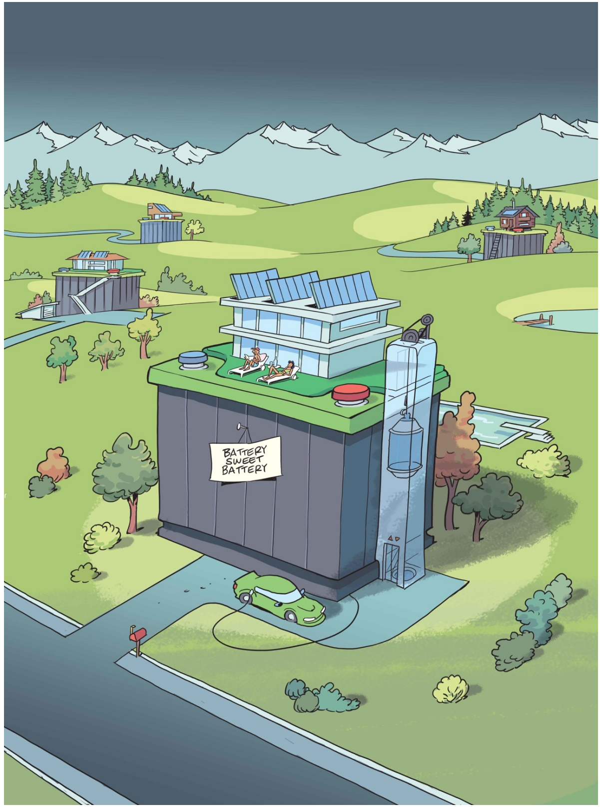
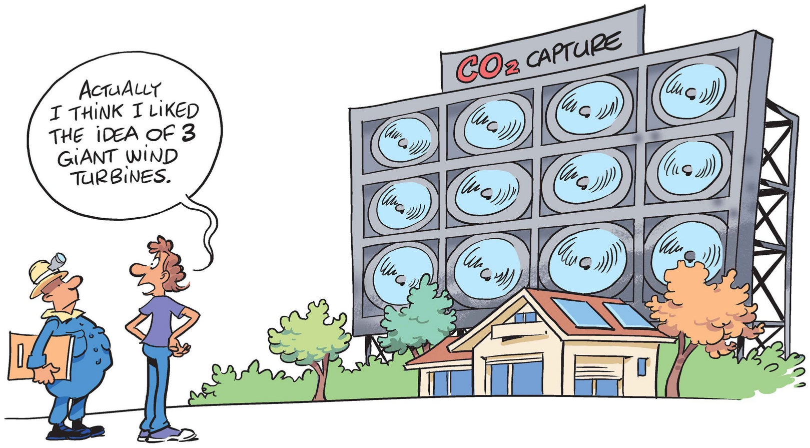
Technological and Data-Driven Improvements



EPFL longread "Energies Go Green"

- Advanced Forecasting:
  - Integration of AI/ML with climate model outputs to predict resource availability.
  - Helps schedule maintenance, reduce downtime, enhance dispatch planning.
- Real-Time Monitoring:
  - Use of SCADA systems to adjust operation under extreme conditions.
  - Increased automation for proactive climate adaptation.

Socioeconomic and Governance Considerations

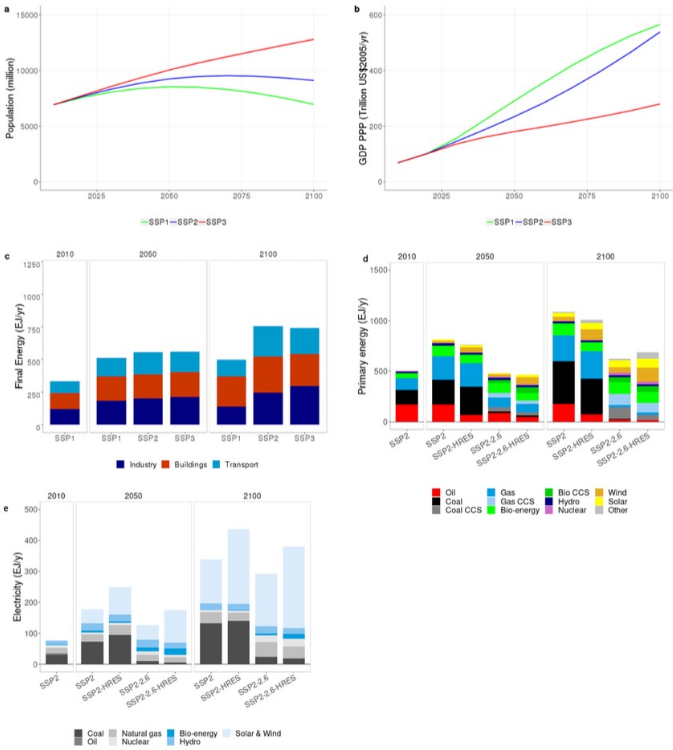


EPFL longread "Energies Go Green"

- Public Acceptance:
  - Community engagement to reduce opposition (e.g., wind turbines, biomass plantations).
- Transboundary Cooperation:
  - Shared river basins (e.g., Nile, Mekong) require joint climate-resilient hydropower frameworks.
- Equity & Justice:
  - Policy must address uneven climate impacts in developing regions.

AGENDA

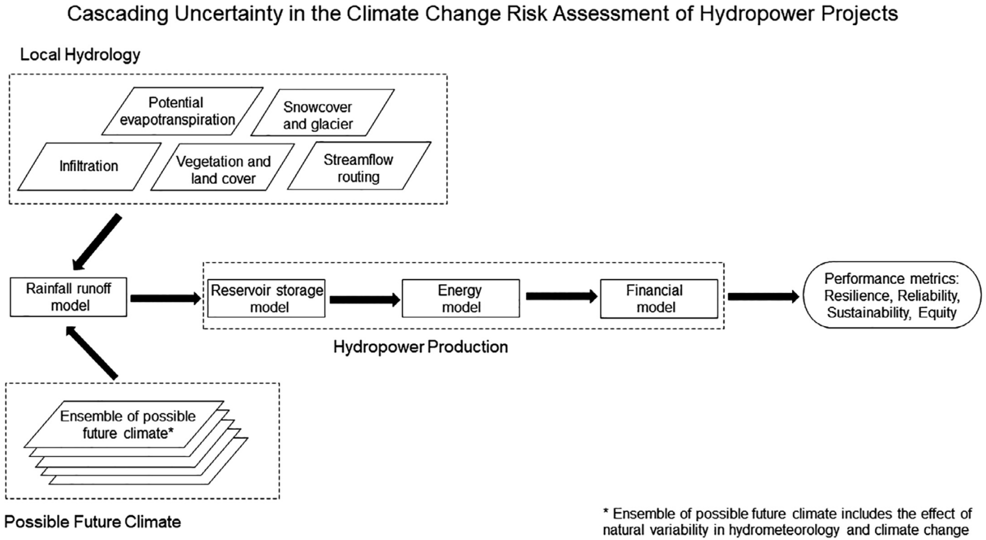
Integrating Climate Variables in Energy Models



Shared Socioeconomic Pathways (SSPs) assumptions for IMAGE
Climate change impacts on renewable energy supply, Gernaat et al. 2021

- Approaches:
  - GCM–RCM coupling for downscaling climate data to local conditions (Yang et al., 2022).
  - Incorporation of temperature, wind speed, precipitation, and extreme event likelihood into energy system equations.
- Case Study:
  - Europe-wide modeling (Solaun & Cerdà, 2019) to map changes under RCP 2.6 vs. 8.5.

Uncertainty Quantification & Scenario Analysis



Model framework for climate change risks assessment of hydropower projects. Possible future climate includes the effect of natural variability and climate change
Climate change and the hydropower sector: A global review, Wasti et al. 2022

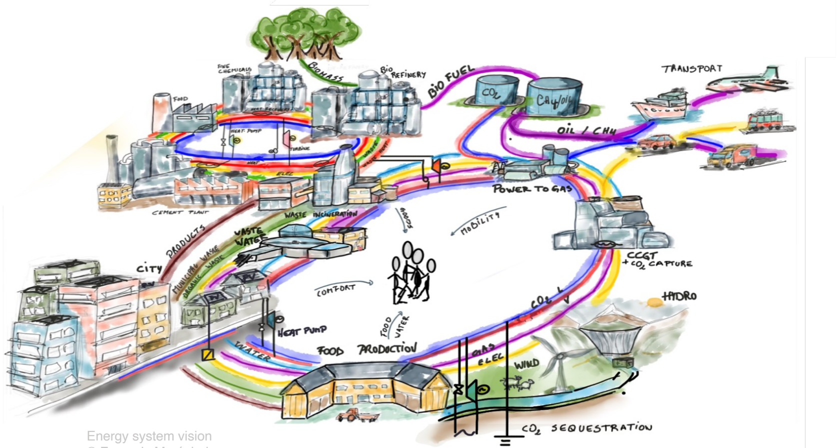
- Key Frameworks: RCPs (2.6, 4.5, 6.0, 8.5), SSPs for socioeconomic context.
- Multi-GCM Ensembles:
  - E.g., HadGEM2, MIROC5, CNRM-CM5, IPSL-CM5A—each can yield different wind/solar/hydro projections.
  - Variability in results underscores the need for robust planning.
- Confidence Intervals:
  - ±10–40% range for wind/hydro potential changes across GCMs (Gernaat et al., 2021).

Multi-Objective Optimization for Adaptation

- Incorporating Climate Resilience:
  - Typical objectives: Cost minimization, GHG reduction, reliability, and resilience.
  - Tools like EnergyScope, REMix, or MARKAL.
- Example:
  - Adding a “climate risk” metric to reflect future uncertainties in resource availability or extreme events.

Schnidrig*, Souttre*, Chuat* et al. 2023, *Between Green Hills and Green Bills: Unveiling the Green Shades of Sustainability and Burden Shifting through Multi-Objective Optimization in Swiss Energy System Planning*, Journal of Environmental Management

Advanced Optimization & Modeling Examples



Energy system vision
© François Maréchal

- Coupled Water–Energy Models:
  - Co-optimization of reservoir operations for electricity, irrigation, and flood control.
- Agent-Based and Stochastic Modeling:
  - Representing policy shifts, market transformations, and random climate shocks.
- Computational Advances:
  - High-performance computing enabling finer temporal and spatial resolution.

A G E N D A

Recap of Previous Lectures

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Feedback Effects (RES on Climate)

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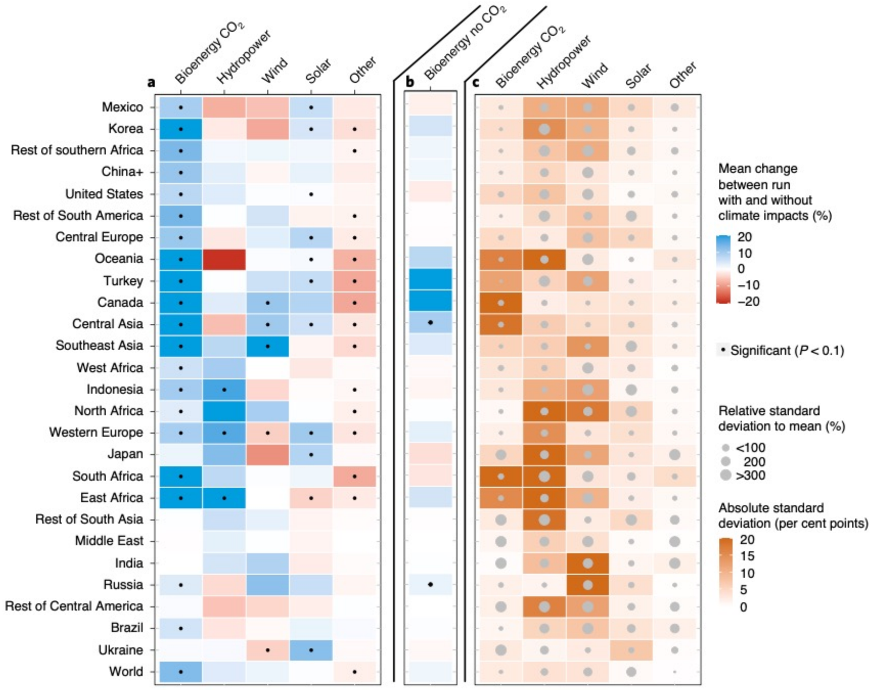
Global Context & Swiss Case Study

Global Perspectives: Regional Highlights

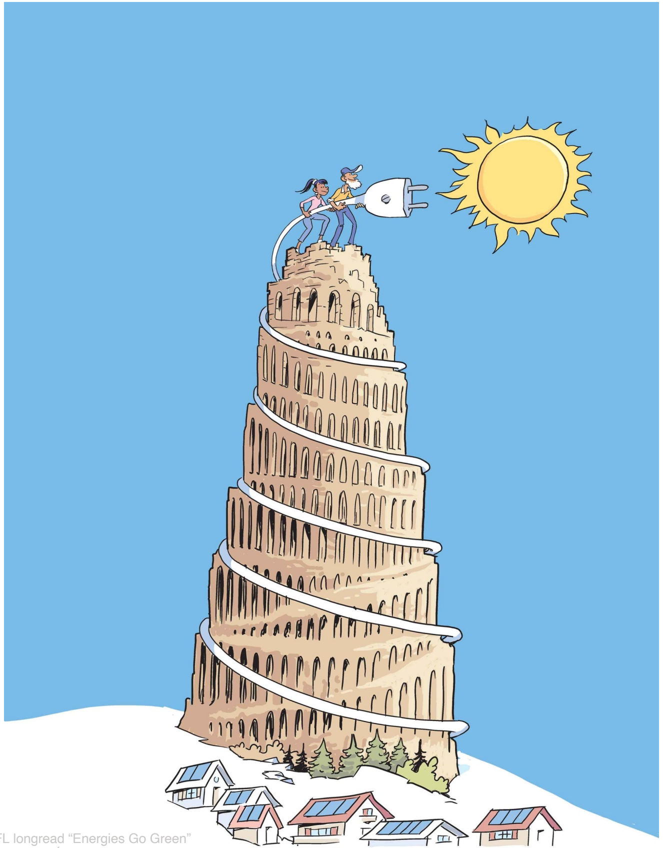


The combined relative effect of climate impacts on cumulative primary energy supply for each IMAGE model region

Climate change impacts on renewable energy supply, Gernaat et al. 2021

- Asia:
  - Glacier-fed hydropower potential in Himalayas—short-term gains, long-term decline (Wasti et al., 2022).
- Africa:
  - Significant solar expansion potential but uncertain rainfall patterns for hydro.
- Europe:
  - North–South wind differences, alpine hydropower sensitivity to snowmelt changes.
- Americas:
  - Drought in western US, potential wind expansions in the Great Plains.

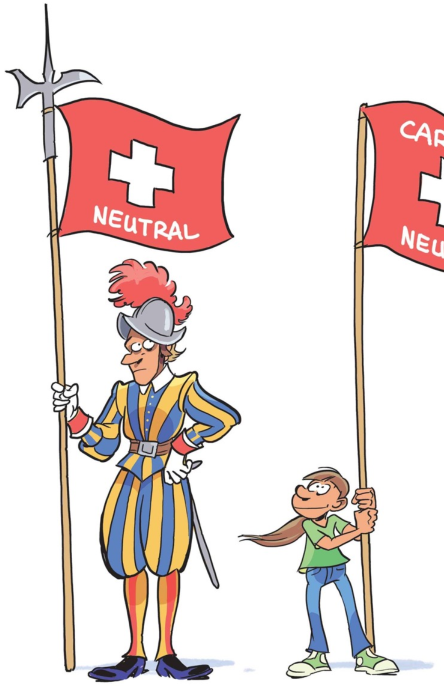
Swiss Energy System Example (Hydro & Solar)



EPFL longread "Energies Go Green"

- Hydropower:
  - Alpine catchments sensitive to earlier snowmelt, potential summer inflow reduction.
  - Existing reservoir infrastructure partially offsets flow variability.
- Solar:
  - High elevation can enhance solar irradiance; temperature effects remain moderate.
  - Seasonal complement with hydropower—summer PV peaks vs. winter reservoir use.

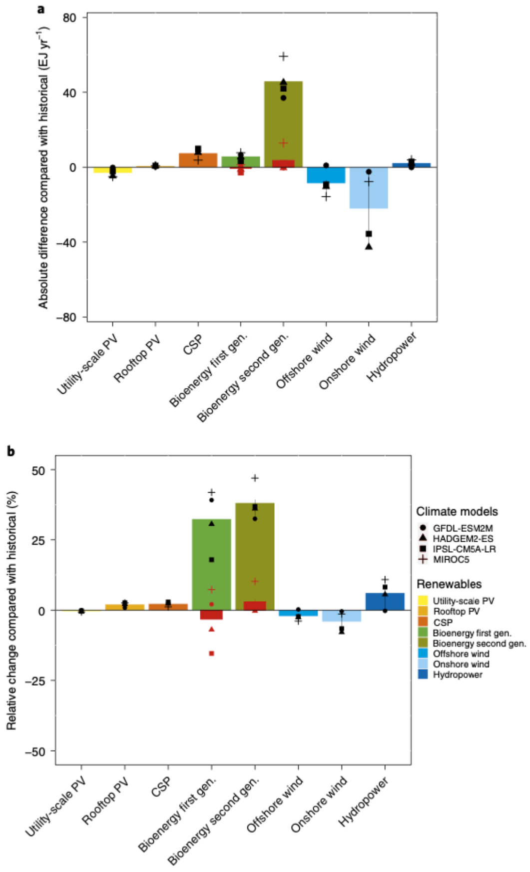
Modeling with EnergyScope



EPFL longread "Energies Go Green"

- Model Integration:
  - Incorporate climate scenarios (e.g., RCP 4.5/8.5) into resource potential modules.
  - Multi-objective approach balancing cost, reliability, decarbonization, and climate resilience.
- Potential Results:
  - Shifts towards hybrid solutions (PV + hydro + storage).
  - Projected better alignment with net-zero targets if seasonal storage is expanded.

Conclusion

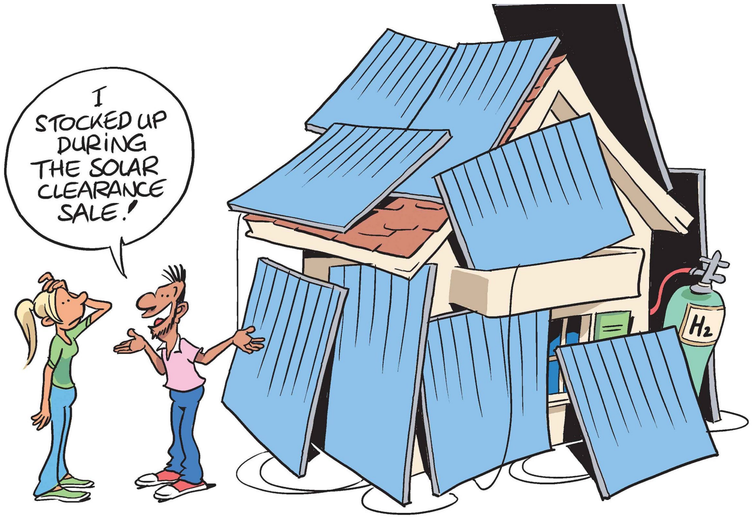


Global mean changes in technical potential for each renewable technology under RCP6.0. *Climate change impacts on renewable energy supply, Gernaat et al. 2021*

- Climate variability significantly affects wind, hydro, and biomass; solar remains relatively resilient but not immune.
- Adaptation strategies and hybrid systems can offset fluctuations in supply and boost reliability.
- Emerging methodologies (GCM–RCM coupling, multi-GCM ensembles, advanced optimization) are crucial for robust planning.
- A balanced, flexible approach involving policy support, technology innovation, and stakeholder engagement can enhance global and local resilience—exemplified by Swiss hydropower–PV synergies.

Discussion

Form groups of 3-4 people and discuss the following points



EPFL longread "Energies Go Green"
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- Which policy instruments most effectively integrate climate adaptation for RES?
- How can advanced forecasting tools mitigate resource variability risks?
- What are the best practices for multi-objective planning in uncertain climates?