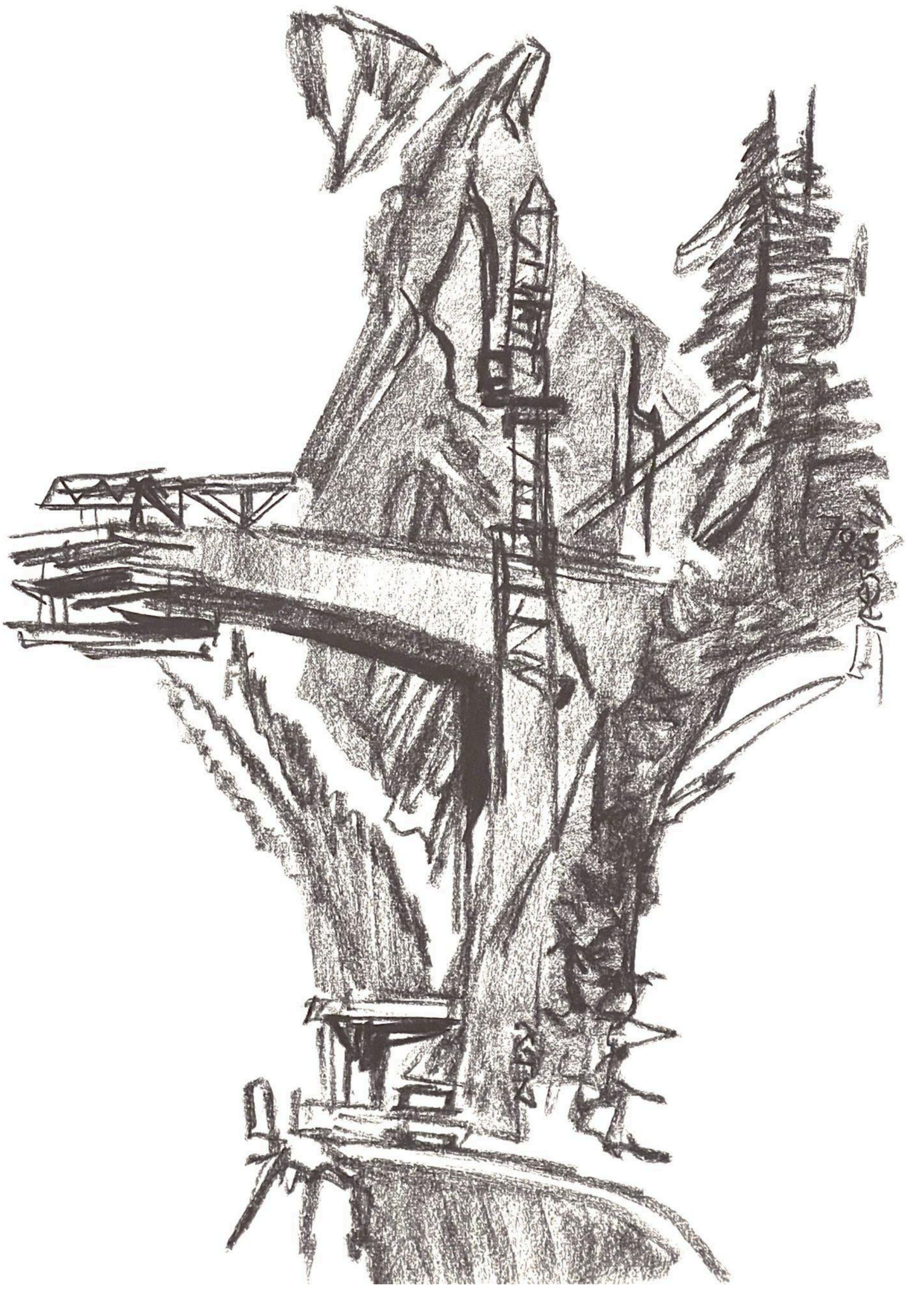
ENV-421 - project description

Towards Sustainable Energy Futures



Case study Conception

This module is designed to equip students to **understand sustainable energy systems** through a multidisciplinary and holistic approach. By integrating theoretical knowledge with practical application, students will develop the skills necessary to design, analyze, and optimize energy systems that are economically viable, environmentally sustainable, and socially acceptable.

Pedagogic Goals

1. **Holistic Understanding:**
   Develop the ability to view energy-related challenges from a systemic perspective, considering technological, economic, environmental, and climate resilience dimensions.
2. **Critical Analysis:**
   Enhance critical thinking skills to evaluate the trade-offs and interdependencies in energy system design and transition pathways.
3. **Sustainability Assessment:**
   Learn to assess the environmental impacts of energy technologies using life cycle assessment methodologies.
4. **Resilience and Adaptation:**
   Understand how to integrate climate change projections into energy planning and develop systems robust to future climatic uncertainties.

Interaction with the Tool

1. **Simulation and Modeling:**
   Use the tool to model Switzerland's energy system, adjusting parameters to optimize for cost, environmental impact, and resilience under climate change scenarios.
2. **Iterative Learning:**
   Engage in a three-stage iterative process—techno-economic analysis, environmental optimization, and climate change adaptation—to refine energy system configurations.
3. **Trade-off Identification:**
   Through the iterative approach, students will learn which compromises to make to balance economic, environmental, and climate resilience objectives.
4. **Uncertainty & Sensitivity Characterization:**
   After the iterative process, students will assess the uncertainty of the energy system scenario using techniques such as Monte Carlo simulations to identify robust solutions.
5. **Data Visualization:**
   Export and import data to visualize trade-offs, analyze outputs, and understand the implications of different energy scenarios.
6. **Decision-Making:**
   Utilize the tool to support strategic decision-making by understanding how changes in one aspect of the system affect others.

Introduction

"*We are the first generation to feel the effect of climate change and the last generation who can do something about it*." - Barack Obama.

The urgency for countries worldwide to transition toward sustainable energy systems has never been greater. Climate change, driven by decades of fossil fuel reliance, poses significant risks not only to the environment but also to the security and stability of energy supplies. Europe—and Switzerland in particular—is at the forefront of these challenges. With firm environmental commitments and a long history of utilizing renewable resources, Switzerland is uniquely positioned to lead the transition toward a sustainable energy future. However, the path forward is fraught with challenges that require carefully balancing technological, economic, environmental, and now, climate resilience considerations.

Historically, Switzerland's energy landscape has been characterized by centralized energy production, predominantly from hydroelectric and nuclear sources. While hydroelectric power remains a cornerstone of the country's strategy, opportunities for expanding this resource are limited due to environmental and geographic constraints. The push toward diversifying the energy mix to include solar, wind, and biomass is critical for reducing dependency on imported energy and aligning with Switzerland's 2050 carbon neutrality goals.

This case study invites participants to step into the role of energy planners tasked with designing a future-ready Swiss energy system that is resilient, sustainable, and robust against climate change impacts. Using the EnergyScope tool, participants will navigate through a structured, three-stage iterative process to explore and optimize different energy system configurations. This process will provide insights into the trade-offs and interdependencies in balancing cost-effectiveness, environmental sustainability, and climate resilience.

The Importance of a Holistic Approach

Switzerland's unique position in the heart of Europe comes with both challenges and opportunities. Its mountainous terrain offers substantial potential for decentralized solar power but complicates large-scale wind deployments and grid expansion. Furthermore, while historical analyses emphasized social acceptance, in this module the focus shifts to ensuring that the energy system is resilient to future climate change. This means integrating climate projections—such as rising temperatures, altered wind patterns, and changes in hydrological regimes—into system design and developing adaptive measures to mitigate these impacts.

To address these challenges, this case study is structured into three main iterations:

1. **Iteration 1: Techno-Economic Analysis:**
   Establish a baseline configuration focused on cost and technical feasibility.
2. **Iteration 2: Environmental Optimization:**
   Integrate environmental impact assessments to enhance sustainability.
3. **Iteration 3: Climate Change Impacts and Resilience:**
   Incorporate climate change projections and develop adaptation strategies to ensure the long-term robustness of the energy system.

Each phase builds upon the previous one, enabling participants to deepen their understanding of energy system design and optimization. Participants will use the EnergyScope tool to simulate real-world scenarios, analyze data, and develop solutions that reflect the interconnected nature of technological, economic, environmental, and climate challenges.

By the end of this case study, participants will have a holistic view of the challenges facing Switzerland's energy transition. They will have the analytical skills necessary to propose viable, forward-thinking solutions that are not only cost-effective and environmentally sound, but also resilient to the uncertainties of climate change. This experience prepares participants for future roles in energy policy and engineering and fosters an interdisciplinary mindset crucial for addressing complex sustainability challenges.

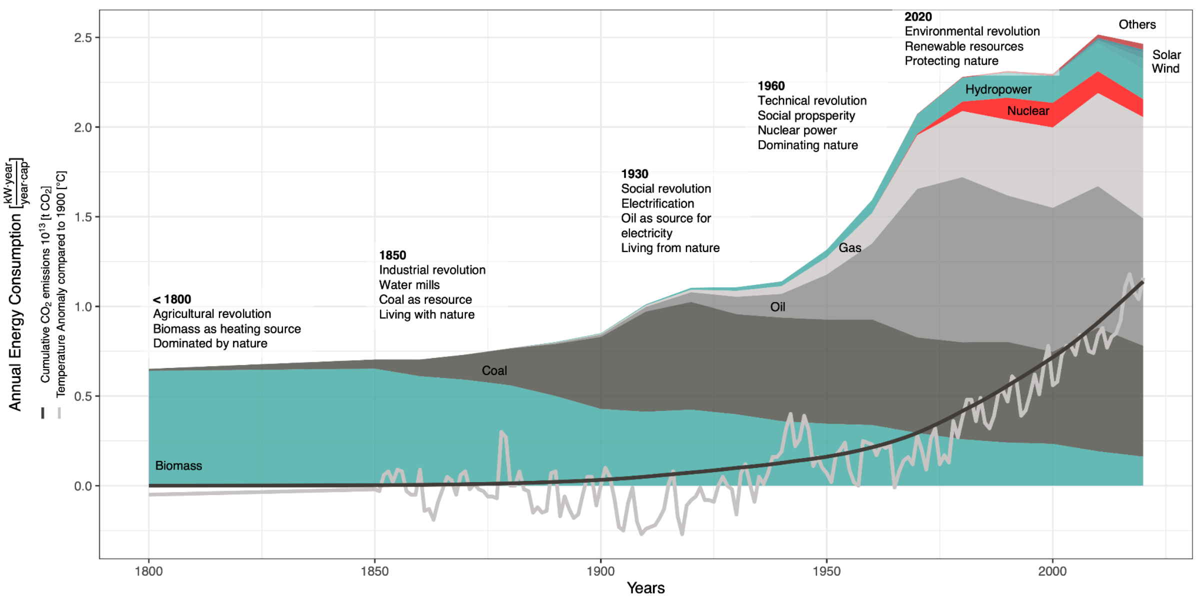
Background

To address Switzerland's energy transition, it is essential to understand its energy system's historical and current context and the challenges that lie ahead. This section provides an overview of global energy transitions, Switzerland's unique energy landscape, and the factors influencing the path toward a more sustainable future.

The Evolution of Energy Systems

Energy systems have dramatically transformed—from early reliance on biomass to complex modern systems dominated by fossil fuels and large-scale centralized power plants. The Industrial Revolution marked a pivotal moment, catalyzing rapid expansion in coal, oil, and natural gas use. These changes fueled unprecedented economic growth and technological advancements but also laid the groundwork for today's climate crisis, characterized by increased greenhouse gas emissions and environmental degradation.

The 20th century introduced nuclear power as an alternative for large-scale, continuous electricity generation with low operational emissions. However, safety risks and waste management challenges eventually prompted a shift toward renewable energy sources like solar and wind in the late 20th and early 21st centuries. While renewables offer cleaner options, they also bring challenges such as intermittency, grid integration, and sensitivity to climate change.



Global energy consumption per capita and temperature evolution.
Each era came with a change in energy sources: The transition from biomass-dominated energy sources to fossil fuels and, most recently, to a growing share of renewables is apparent. Biomass, which accounted for approximately 90%of energy consumption in the 1800s, decreased to less than 40% by the 1900s when coal, oil, and gas became dominant. Renewables have become more significant in the last two decades, reaching over 10% of global energy consumption. Cumulative CO2 emissions and temperature anomalies have been correlated to anthropogenic activities by the IPCC.
NOAA calculated the temperature anomaly using the reference year 1900. The specific energy use is determined as the ratio between annual energy consumption Wyear/year and the respective population [Goldewijk et al. 2017]. The CO2 emissions are calculated as the cumulative sum of emissions since 1800.

The Swiss Energy Context
Switzerland’s energy system is defined by its extensive use of hydroelectric power, which supplies a substantial portion of its electricity. Nuclear power has historically complemented hydropower, but recent policy decisions—exemplified by the Swiss Energy Strategy 2050—call for phasing out nuclear power. The strategy emphasizes reducing carbon emissions, enhancing energy efficiency, and integrating more renewable energy sources. However, Switzerland’s mountainous topography and densely populated areas create logistical challenges for deploying technologies like solar and wind on a large scale.

Key Challenges in the Transition
Security of Supply and Stability:
Ensuring a reliable energy supply while integrating high shares of variable renewable energy requires balancing generation with demand management. Complementary measures such as energy storage and flexible backup systems are critical.

Economic Constraints:
Transitioning to a renewable-based energy system involves significant investment. Managing capital and operational costs while attracting both public and private funding is a complex challenge.

Environmental and Sustainability Goals:
While renewables reduce greenhouse gas emissions, their deployment must be carefully managed to minimize adverse environmental impacts such as land-use conflicts and resource depletion.

Climate Change Impacts and Resilience:
Future climate change is expected to alter resource potentials and system performance. Rising temperatures, changing wind patterns, and hydrological shifts necessitate that the energy system be designed with built-in resilience and adaptive capacity.

Opportunities for Progress
- **High Renewable Potential:**
  Advances in distributed solar PV and improved wind turbine designs could unlock considerable renewable energy potential.
- **Strong Infrastructure Foundation:**
  Existing hydroelectric power provides a reliable backbone, which can be enhanced with new technologies such as battery storage and power-to-gas systems.
- **Policy and Public Engagement:**
  Switzerland’s direct democracy offers a unique opportunity to engage the public in energy planning, ensuring that policies reflect collective priorities and that the system is resilient to climate uncertainties.

Problem Statement - Concept

Switzerland faces a complex challenge in transitioning its energy system to meet ambitious sustainability targets while ensuring long-term resilience against climate change. The problem is multifaceted, encompassing economic feasibility, environmental impacts, and the need to adapt to climate-induced changes. This case study defines the scope and objectives, emphasizing the need for an iterative approach to developing a comprehensive and resilient energy system configuration.

Defining the Core Challenge

The primary challenge is to design an energy system that meets future demand, reduces carbon emissions, and remains robust under a range of climate scenarios. The EnergyScope tool provides the analytical framework for exploring various configurations and evaluating their implications through a structured, three-part iterative pro.

Key Objectives of the Case Study

This case study challenges participants to design and evaluate an energy system that meets Switzerland's projected energy demands for 2050 by balancing economic, environmental, and climate resilience considerations. The main objectives are:

1. **Develop a Techno-Economic Baseline:**
   Construct an energy system configuration that is cost-effective and meets energy service demands using current and emerging technologies. Identify key economic trade-offs and technical constraints such as resource potentials, grid limitations, and investment requirements.
2. **Incorporate Environmental Objectives:**
   Refine the baseline configuration by integrating environmental impact assessments (e.g., via Impact World+). Analyze trade-offs between economic performance and environmental sustainability, quantify emissions, and assess the life cycle impacts of various energy technologies.
3. **Adapt for Climate Change Impacts and Resilience:**
   Address the challenges of future climate change by evaluating how altered resource potentials and demand profiles affect system performance. Develop adaptation strategies to enhance system resilience—such as integrating advanced cooling for PV panels, diversified wind turbine designs, and enhanced storage capacity—and assess the system's vulnerability under different climate scenarios.

Detailed Description

The project is built on three iterative processes that help develop critical thinking and scenario planning skills:

- Develop Critical Thinking: Analyze how changes in one aspect of the energy system affect others, fostering a holistic understanding of energy planning.
- Engage in Scenario Planning: Use EnergyScope to explore “what-if” scenarios highlighting the interplay between economic, environmental, and social considerations.
- Propose Balanced Solutions: Create a comprehensive energy system proposal that is technically feasible, economically viable, environmentally responsible, and socially acceptable.

Iteration 1: Techno-Economic Analysis

Objective:

Develop a baseline configuration that is both economically viable and technically feasible.

Key Components:

- Analyze available renewable and non-renewable resources, including solar, wind, hydroelectric, and biomass.
- Consider technological limitations such as efficiency, capacity factors, and integration requirements.
- Model economic parameters including CAPEX, OPEX, and fuel costs, and set CO_2 emission limits based on policy targets.

Methodology:

Use the EnergyScope tool to construct a model of the Swiss energy system, adjusting parameters to optimize for cost while meeting projected energy demands.

Expected Outcomes:

- A techno-economic baseline configuration that meets demand and complies with emission targets.
- Insights on cost drivers and key technical constraints.

Iteration 2: Environmental Optimization

Objective:

Enhance the baseline configuration by integrating environmental impact assessments to minimize ecological impacts while maintaining economic feasibility.

Key Components:

- Apply environmental impact methodologies (such as Impact World+) to assess indicators like human health, ecosystem quality, resource depletion, and water availability.
- Implement emission reduction strategies including carbon pricing and emissions caps.
- Conduct life cycle assessments covering production, operation, and decommissioning phases.

Methodology:

Adjust the baseline configuration from Iteration 1 by applying environmental constraints and multi-objective optimization to balance cost and environmental impacts.

Expected Outcomes:

- An environmentally refined configuration with reduced emissions and environmental impacts.
- A clear trade-off analysis between economic costs and environmental benefits.

Iteration 3: Climate Change Impacts and Resilience

Objective:

Adapt the energy system configuration to account for future climate change impacts and enhance system resilience.

Key Components:

- **Climate Parameters:** Modify demand profiles to reflect climate-induced changes (e.g., increased cooling demand, altered heating requirements). Adjust renewable resource potentials to simulate the effects of climate change (e.g., reduced hydro availability due to glacier melt, changes in solar irradiance and wind patterns).
- **Resilience Metrics:** Evaluate system vulnerabilities and quantify resilience indicators, such as flexibility scores and reliability indices.
- **Adaptation Strategies:** Propose technological modifications (e.g., advanced cooling for PV panels, diversified wind turbine designs, integrated energy storage) and operational measures to mitigate adverse climate impacts.

Methodology:

Use the EnergyScope tool to incorporate climate change projections and run simulations that evaluate the energy system's performance under various climate scenarios. Identify vulnerabilities and determine adaptation measures to enhance resilience.

Expected Outcomes:

- A climate-adapted energy system configuration that maintains performance under projected future conditions.
- Detailed adaptation strategies and resilience indicators that inform policy and investment decisions.

Step-by-step Guide

Overview and Purpose

The EnergyScope tool is designed to help you develop a robust and resilient energy system configuration tailored to the Swiss context. The tool guides you through three sequential iterations, each focusing on a specific aspect of energy system planning:

Iteration 1: Techno-Economic Assessment

Iteration 2: Environmental Sustainability

Iteration 3: Climate Change Impacts and Resilience

This stepwise (myopic) approach ensures that you focus on one set of challenges at a time. As you progress, each iteration builds on the results of the previous one, allowing you to refine your scenario gradually. At every stage, you will interact with sliders, input fields, and visualizations that help you define key parameters, run simulations, and compare outcomes. You are encouraged to explore the tool, document your assumptions, and answer the guiding questions to better understand the implications of your decisions.

Home Page and User Login

Login Process:

Use your assigned credentials (e.g., your Gaspar account) to log in. Once logged in, your progress is saved automatically as you work through the iterations.

Home Page Overview:

When you first log in, if no configurations have been created yet, the home page will be empty. Once you create and validate a configuration, it will appear as an entry in the parallel coordinates display. Here, you can compare finalized iterations, select a configuration to review or modify, download, share, or upload configurations with team members.

Creating a New Configuration

Click the “Create Configuration” button on the home page to start a new scenario. This will take you directly into Iteration 1, where you will begin by establishing a techno-economic baseline for the energy system.

Iteration 1: Techno-Economic Assessment

Introduction and Context:

In this first phase, you will build a baseline energy system configuration based solely on techno-economic considerations. Your goal is to define the key demands (such as population growth, building energy use, industrial energy intensity, and transport requirements) and available resources (such as energy imports, local biomass, and renewable potentials). Additionally, you will select the primary energy technologies available (e.g., nuclear, geothermal, hydro, wind, and photovoltaic systems) and set the carbon neutrality constraint. This iteration focuses on cost minimization, investment decisions, and meeting overall energy demand.

Challenges:

- Defining realistic demand scenarios for 2050 based on socio-economic parameters.
- Balancing available resource inputs with technological capacities.
- Optimizing the energy mix while keeping total system costs low and meeting emission targets.

How to Proceed:

1. **Access the Demand Definition Tab:**
    - Use the sliders to input parameters such as population (in millions), average appliance consumption (kWh/year), building-specific demand (kWh/m²), living area per capita (m²), GDP growth, industry energy intensity, and transport demands.
    - Each slider comes with a “?” icon. Hover over the icon to read detailed explanations that clarify what each parameter represents and its impact on the system.
2. **Configure Resources:**
    - Move to the Resources tab to set values for external imports (e.g., coal, diesel, gasoline, hydrogen, etc.) and local resources (e.g., waste, wet biomass, wood).
3. **Select Primary Energy Technologies:**
    - In the Technologies tab, adjust the available capacities for technologies like nuclear, geothermal, hydro (dam and run-of-river), wind, and PV.
4. **Set the Carbon Neutrality Constraint:**
    - Define the per capita carbon balance to reflect the carbon neutrality goal. This constraint is essential for ensuring that your configuration aligns with long-term climate targets.
5. **Run the Optimization:**
    - Once all parameters are set, click “Run Calculation” to generate your baseline configuration. The tool will optimize the system based on total cost minimization while meeting your input criteria.
6. **Review the Results:**
    - Visualize the outcomes using the provided graphs:

    - **Parallel Coordinates:** Compare your scenario with reference cases (such as 2020, low, high projections).
    - **Sankey Diagram:** See how energy flows between different sectors.
    - **Treemap:** Examine the distribution of demand across sectors.
    - **Cost and Carbon Bar Plots:** Analyze investment, operation, and maintenance costs alongside Scope 1 carbon emissions.

Guiding Questions for Iteration 1:

- What assumptions have you made about population and economic growth, and how might these affect overall energy demand?
- How do your selected resource and technology parameters influence the balance of the energy system?
- Which factors are the primary cost drivers in your baseline configuration?
- Are there any constraints (e.g., grid capacity or emission limits) that significantly influence the outcome?

Iteration 2: Environmental Sustainability

Introduction and Context:

In Iteration 2, you build upon your techno-economic baseline by integrating environmental impact assessments. This phase involves incorporating environmental constraints using the Impact World+ methodology. Your task is to refine the baseline configuration to reduce ecological impacts, such as greenhouse gas emissions, resource depletion, and water usage, while still maintaining cost-effectiveness.

Challenges:

- Balancing the trade-offs between economic costs and environmental sustainability.
- Adjusting technology and resource choices to minimize environmental impacts.
- Understanding how changes in the system affect overall environmental performance.

How to Proceed:

1. **Transition from Iteration 1:**
    - Click “Use these results for next step” to carry your baseline configuration into Iteration 2.
2. **Adjust Environmental Parameters:**
    - Use the new set of sliders that pertain to environmental indicators. These might include settings related to emissions, water usage, resource depletion, and other impact categories.
    - Hover over the “?” icons next to each slider to review detailed explanations and suggested ranges.
3. **Run the Environmental Optimization:**
    - The tool will generate six different configurations using Single-Objective Optimization (SOO) that minimize environmental impacts while considering cost.
    - Visualize the results with spider (radar) plots, updated Sankey diagrams, parallel coordinates, and bar plots.
4. **Analyze Trade-Offs:**
    - Compare your environmentally optimized configuration with your techno-economic baseline and the 2020 reference case.
    - Assess how specific environmental indicators change with different resource and technology choices.

Guiding Questions for Iteration 2:

- Which environmental indicators are most sensitive to changes in your configuration?
- How do modifications in technology and resource selections affect overall environmental impact?

- What trade-offs exist between reducing emissions and maintaining cost-effectiveness?
- How can the insights from the spider plots and other visualizations guide your decision-making?

Iteration 3: Climate Change Impacts and Resilience

Introduction and Context:

Iteration 3 focuses exclusively on assessing the resilience of your energy system configuration to future climate change impacts. In this phase, you will simulate how changes in climate parameters (such as temperature anomalies, wind variability, and hydrological shifts) affect system performance. The goal is to identify vulnerabilities and develop adaptation strategies that ensure your energy system remains robust under various climate scenarios (e.g., SSP2, SSP3).

Challenges:

- Adjusting demand profiles to account for increased cooling demand or reduced heating demand.
- Modifying resource potentials to reflect climate impacts on hydro, solar, and wind availability.
- Quantifying the effects of climate change on system costs and emissions.
- Developing concrete adaptation strategies (e.g., advanced cooling systems for PV panels, diversified wind turbine designs, enhanced energy storage).

How to Proceed:

1. **Transition to Iteration 3:**
    - Click “Use these results for next step” from Iteration 2 to move into the climate change impacts phase.
2. **Adjust Climate Change Parameters:**
    - Use the climate sliders to modify parameters such as:
    - Annual changes in biomass availability.
    - Annual precipitation shifts affecting hydropower.
    - Deviations in solar irradiance and wind speed (both annual and seasonal).
    - Temperature anomalies that influence cooling and heating demands.
    - Each slider includes a detailed “?” icon explaining the parameter and its potential impact on the energy system.
3. **Simulate Climate Scenarios:**
    - The tool will update your energy system configuration based on the new climate parameters.
    - Review the updated visualizations:
        - **Sankey Diagram:** Reflects changes in energy flows due to climate effects.
        - **Bar Plots:** Show variations in total cost and CO_2 emissions.
        - **Treemap:** Displays changes in demand composition.
        - **Parallel Coordinates:** Compare the climate-impacted configuration with your previous iterations.
4. **Resilience Assessment and Adaptation:**
    - Analyze vulnerabilities in your system. For example, assess how a reduction in solar efficiency due to higher temperatures or changes in wind speed affects overall performance.

- Propose adaptation strategies, such as:
- Installing advanced cooling systems for PV panels.
- Diversifying wind turbine designs.
- Enhancing energy storage capacity to buffer fluctuations.
- Document your proposed measures and explain how they help maintain system performance under future climate conditions.

Guiding Questions for Iteration 3:

- How do increased temperatures and altered wind patterns affect the performance of your renewable technologies?
- What vulnerabilities does your energy system exhibit when exposed to climate change scenarios (e.g., SSP2 vs. SSP3)?
- Which adaptation strategies appear most effective in mitigating these impacts?
- How does the revised cost and emission profile compare with the baseline and environmentally optimized configurations?
- What further uncertainties need to be addressed to ensure the long-term resilience of your energy system?

Saving and Sharing Your Configuration

- Once you are satisfied with your climate-adapted configuration, click the **“Save Configuration”** button.
- You will be prompted to enter a name for your configuration. This name will then appear on the home page.
- From the home page, you can:
    - View and compare your saved configurations displayed in the parallel coordinates chart.
    - Select a configuration to load for further modifications.
    - Download or share your configuration with team members.
    - Upload a previously saved configuration to continue working on it.

Iterative Workflow Summary

1. **Home Page:**
    - Log in and, if no configurations exist, click **“Create Configuration”**.
2. **Iteration 1 – Techno-Economic Assessment:**
    - Define demands, resources, technologies, and carbon neutrality constraints using the provided sliders.
    - Run the optimization to generate your baseline configuration.
3. **Iteration 2 – Environmental Sustainability:**
    - Integrate environmental impact indicators.
    - Adjust parameters to minimize environmental impacts while balancing costs.
    - Compare and analyze your configuration using visual tools.
4. **Iteration 3 – Climate Change Impacts and Resilience:**
    - Adjust climate change parameters to simulate future conditions.
    - Evaluate system vulnerabilities and propose adaptation strategies.
    - Visualize and compare the climate-impacted configuration with previous iterations.
5. **Saving and Sharing:**
    - Save your final configuration, name it, and access it from the home page to modify, share, or compare.

User Support and Documentation

- Each slider and input field includes a **”?”** icon for detailed explanations.
- A comprehensive user guide is available in the tool’s help section, offering additional context, best practices, and troubleshooting tips.
- Collaboration features allow you to share configurations with team members and to upload/download scenarios for further analysis.
- For further assistance, please refer to the in-tool documentation or contact your project supervisor.

Conclusion

By following this step-by-step guide, you will systematically develop a robust energy system configuration for Switzerland. This process begins with establishing a techno-economic baseline, refines the system through environmental optimization, and ultimately ensures resilience by incorporating climate change impacts. Throughout, you are encouraged to reflect on the guiding questions, document your assumptions and decisions, and use the visual tools provided to compare various scenarios. This iterative approach not only strengthens your understanding of energy system planning but also prepares you for effective, future-proof decision-making.

If you have any questions or need further clarification, please consult the help documentation or reach out to your project supervisor.