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IPESE
Industrial Process and Energy Systems Engineering

Hes·so // VALAIS WALLIS
School of Engineering

CIRAIG

ENV-421

Energy Technologies

Jonas SCHNDIRIG

Week 7

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

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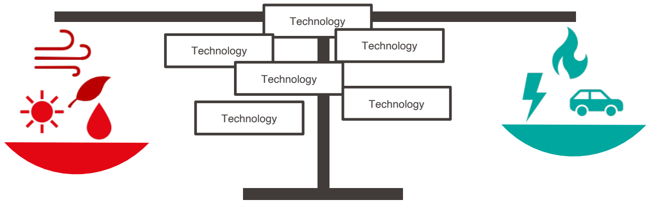
A G E N D A

Energy system modeling - EnergyScope



Resources

Costs & Emissions
Annual availability

Technology

Fossils & Renewables
Investments & O&M
Efficiencies & Emissions
Storage

Energy demands

Illustration of the energy system modeling principle

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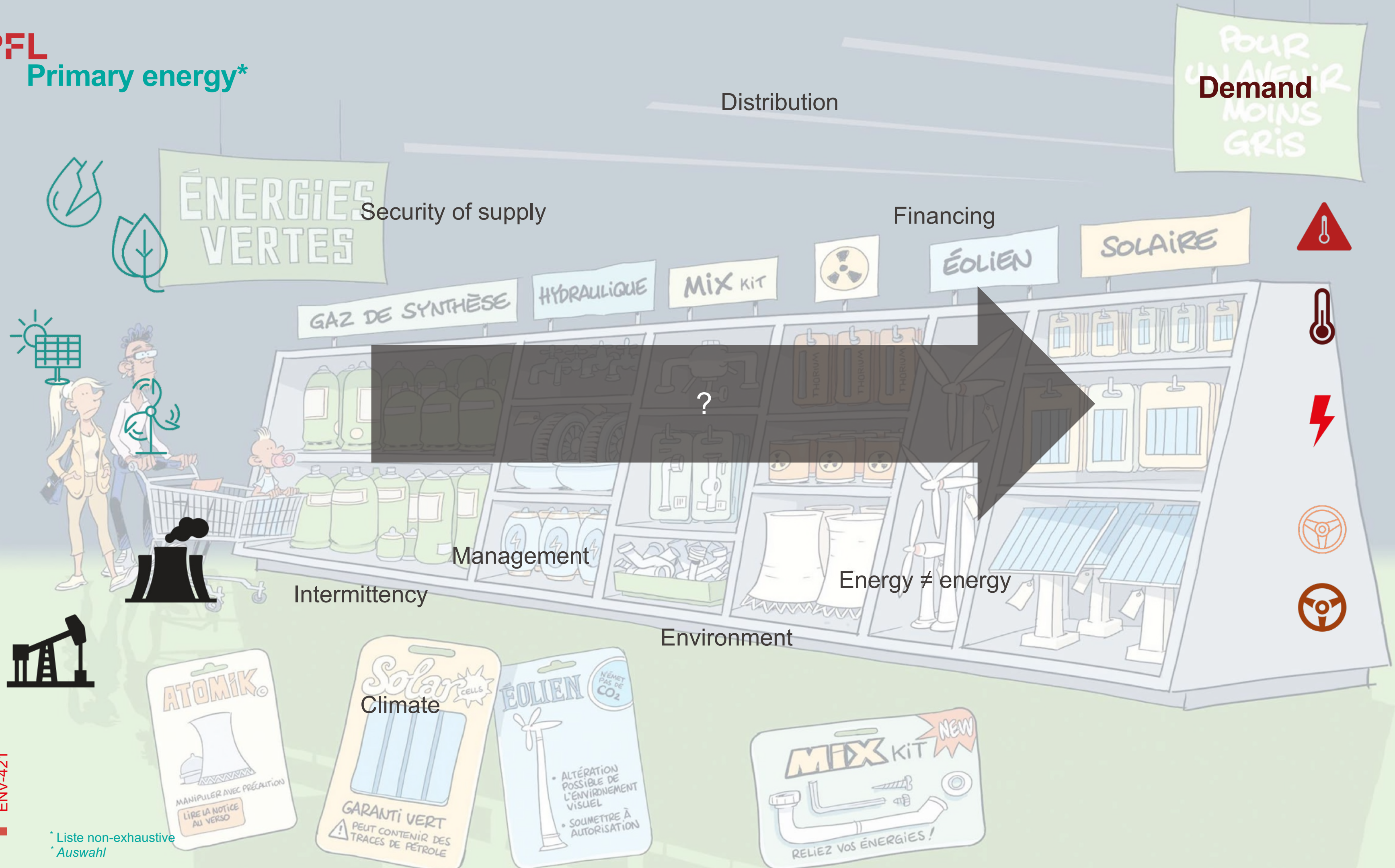
Primary energy*



* Liste non-exhaustive
* *Auswahl*

Energy system modeling - EnergyScope

Resources

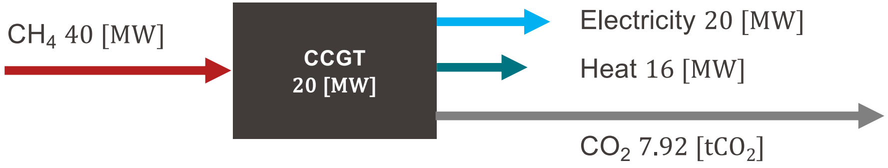
Cost & emissions
Yearly availability

Technologies

Fossils and renewables
Investement and O&M cost
Efficiencies, emissions
Storage

Energy demand

Technology example: *Combined Cycle gas turbine*



Energy system modeling - EnergyScope

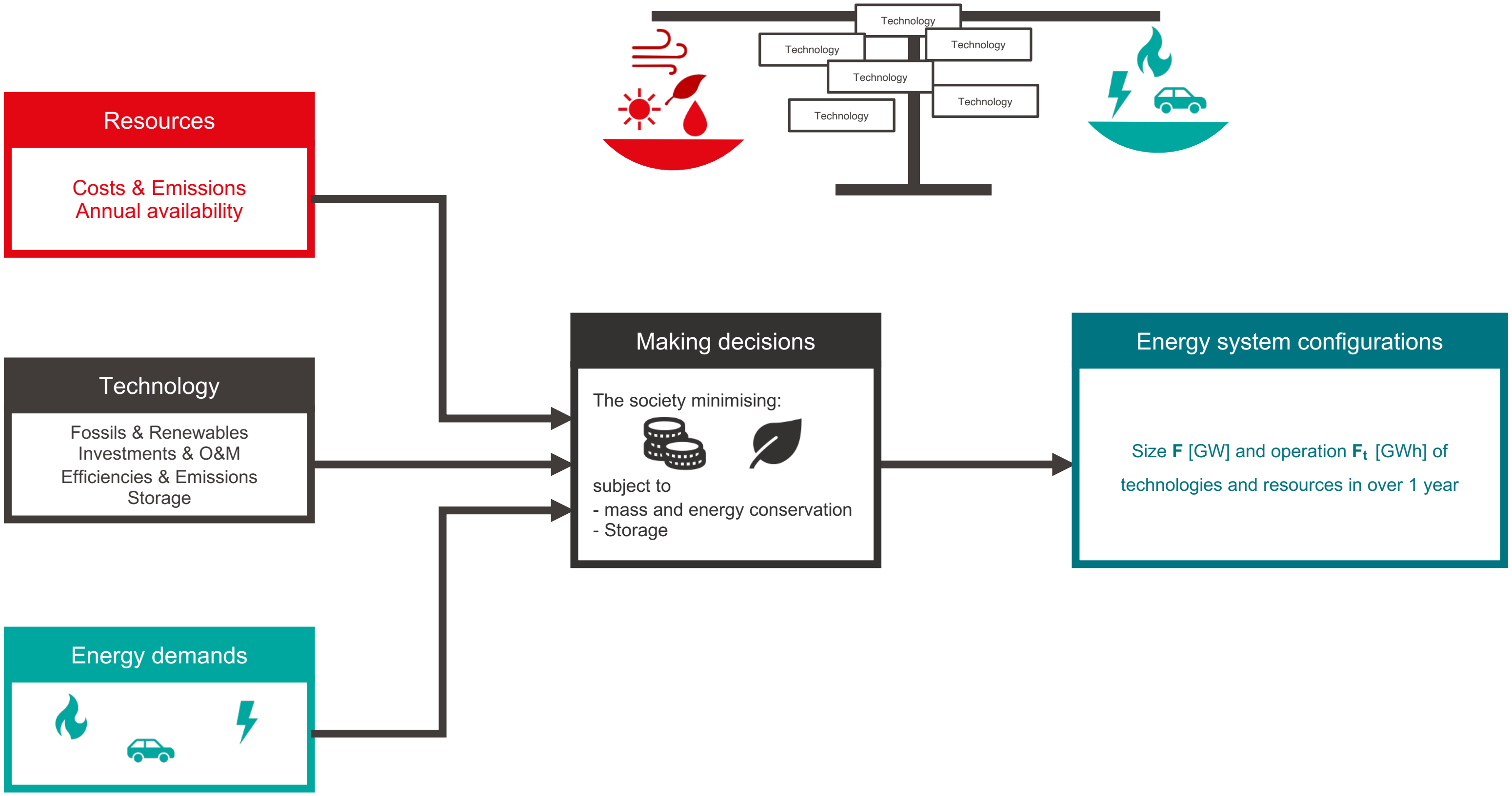


Illustration of the energy system modeling principle

Energy system modeling
The life of a technology

Installation **F** [GW] and operation $\mathbf{F_t}$ [GWh] of technologies and resources in over 1 year

Investment
25 kCHF

Annual Service
1000 CHF/year
Fuel
1.82 CHF/l

Disposal (Transport)
100 CHF

Construction Cost

Maintenance Cost
Exploitation Cost

Demolition and Disposal Cost

Construction → Use → EoL

Construction Impact

Exploitation Impact

Demolition and Disposal impact

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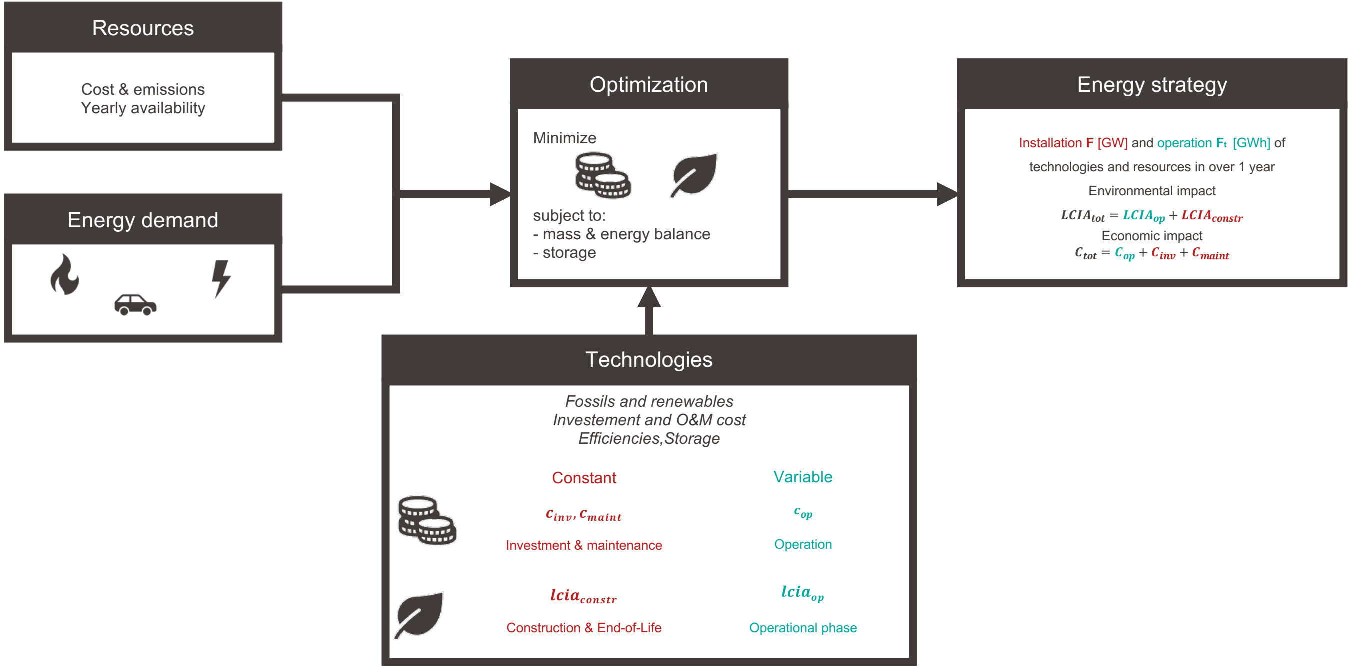
Energy system modeling

Technologies' impacts within the energy system



Graphical representation of the methodology followed integrating LCIA indicators into ES. The green steps at the bottom of the figure illustrate the adaptation of the Life Cycle Inventory (LCI) to the ES technologies to be split into variable and constant impact to allow the optimization of economic (red) and environmental (green) variables.

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, 2024

Energy system modeling - EnergyScope

Resources

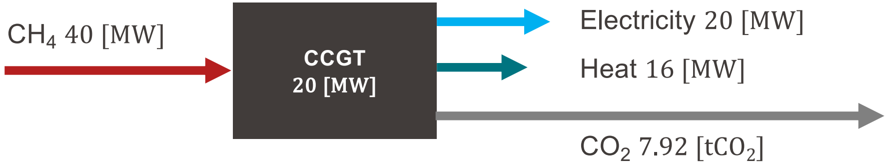
Cost & emissions
Yearly availability

Technologies

Fossils and renewables
Investement and O&M cost
Efficiencies, emissions
Storage

Energy demand

Technology example: *Combined Cycle gas turbine*



Investment costs:	1339.67 [kCHF/MW]
Maintenance costs:	40.08 [kCHF/MW]
Construction emissions:	490.88 [t CO_2/MW]
Lifetime:	24 [y]
Annual operation factor:	85 [%]

Energy system modeling
Economic characterization

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Investment
25 kCHF
Disposal (Transport)
100 CHF

Annual Service
1000 CHF/year

Fuel
1.82 CHF/l

- Investment + EoL

$$C_{inv}\ [\text{CHF/year}] = c_{inv}\left[\frac{\text{CHF}}{\text{kW}}\right]\cdot F[\text{kW}]\cdot \tau\left[\frac{1}{\text{year}}\right]$$

  - c_{inv}: *specific investment cost*
  - F: *installed size*
  - $\tau = \frac{i(1+i)^n}{(1+i)^n-1}$ *annualization factor*
  - i: *interest rate*
  - n: *lifetime*

- Maintenance

$$C_{maint}\left[\frac{\text{CHF}}{\text{year}}\right] = c_{maint}\left[\frac{\text{CHF}}{\text{kW}\cdot\text{year}}\right]\cdot F[\text{kW}]$$

  - c_{maint}: *specific maintenance cost*
  - F: *installed size*

- Operation

$$C_{op}\left[\frac{\text{CHF}}{\text{year}}\right] = c_{op}\left[\frac{\text{CHF}}{\text{kWh}}\right]\cdot F_t[\text{kW}]\cdot t_{op}[h]$$

  - c_{op}: *specific operational cost*
  - F_t: *technology use during period* t
  - t_{op}: *period duration*

Energy system modeling
Economic characterization

Investment
25 kCHF

Disposal (Transport)
100 CHF

Annual Service
1000 CHF/year

Fuel
1.82 CHF/l

- Investment + EoL

$$C_{inv}\,[\mathrm{CHF/year}] = c_{inv}\left[\frac{\mathrm{CHF}}{\mathrm{kW}}\right] \cdot F[\mathrm{kW}] \cdot \tau[\frac{1}{\mathrm{year}}]$$

  - c_{inv}: *specific investment cost*
  - F: *installed size*
  - $\tau = \frac{i(1+i)^n}{(1+i)^n-1}$ *annualization factor*
  - i: *interest rate*
  - n: *lifetime*

- Maintenance

$$C_{maint}\left[\frac{\mathrm{CHF}}{\mathrm{year}}\right] = c_{maint}\left[\frac{\mathrm{CHF}}{\mathrm{kW{\cdot}year}}\right] \cdot F[\mathrm{kW}]$$

  - c_{maint}: *specific maintenance cost*
  - F: *installed size*

- Operation

$$C_{op}\left[\frac{\mathrm{CHF}}{\mathrm{year}}\right] = \sum_t c_{op}\left[\frac{\mathrm{CHF}}{\mathrm{kWh}}\right] \cdot F_t[\mathrm{kWh}]$$

  - c_{op}: *specific operational cost*
  - F_t: *technology use during period* t

- Total Cost

$$C_{tot} = \sum_{TEC}(C_{inv}[tec] + C_{maint}[tec]) + \sum_{RES} C_{op}\,[res]$$

Calculate the annual cost of the car given in example, assuming an annual usage 20'000 km at a consumption of 5l/100km. The car is leased for 4 years at 0.9% .

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Annual Cost of a Fossil-Fuel Car

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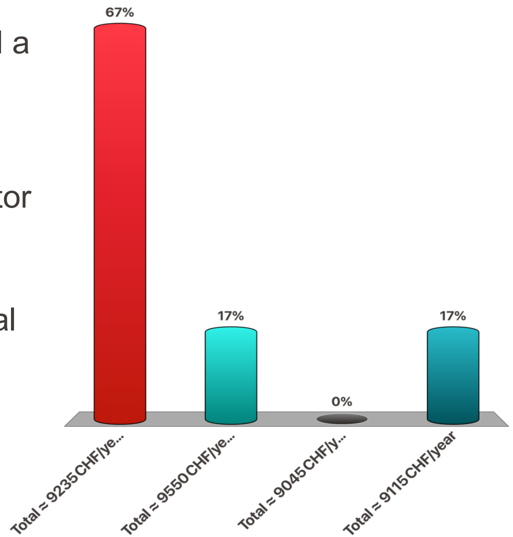
A gasoline car travels 20,000 km/year with a consumption of 5 L/100 km. The fuel price is 1.82 CHF/L. The car's purchase price is 25,000 CHF, financed over 4 years at 0.9% interest, with an annual service cost of 1,000 CHF and a one-time disposal fee of 100 CHF (annualized over 4 years).

(a) Calculate the annual fuel cost.
(b) Compute the annualized lease (capital) cost using the annualization factor $\tau = \frac{i(1+i)^n}{(1+i)^n - 1}$, with P = 25'000 CHF, i = 0.9,% n = 4.
(c) Sum the fuel, lease, service, and disposal costs to obtain the total annual cost.



✓ A. Total ≈ 9235 CHF/year
B. Total ≈ 9550 CHF/year
C. Total ≈ 9045 CHF/year
D. Total ≈ 9115 CHF/year

Annual Cost of a Fossil-Fuel Car

1. **Step (a): Fuel Cost**

- $Fuel\ consumption\ =\ 20'000 \times \frac{5}{100}\ =\ 1000L/year$
- $Fuel\ cost\ =\ 1000L \times 1.82CHF/L\ =\ 1820CHF/year$

2. **Step (b): Lease Payment**

- Calculate using the annuity formula:
  - $(1+i)^n\ =\ (1.009)^4 \approx\ 1.0366$
  - $Payment \approx\ 25'000 \times \frac{(0.009 \times 1.0366)}{(1.0366-1)} \approx\ 25'000 \times \frac{0.00933}{0.0366} \approx\ 25'000 \times 0.255 \approx\ 6375CHF/year$

3. **Step (c): Service and Disposal**
   - Service = 1000 CHF/year; Disposal fee = 100 CHF over 4 years = 25 CHF/year.

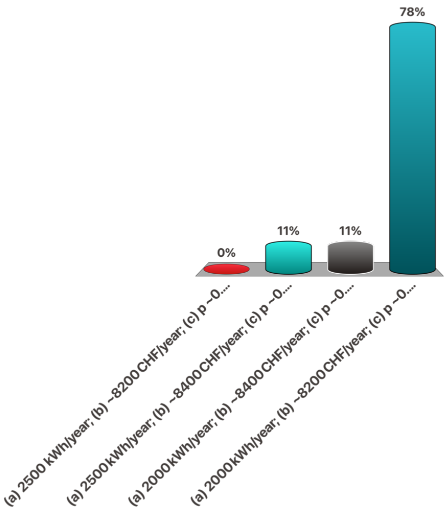
4. **Total Annual Cost:**
   - $1820\ +\ 6375\ +\ 1000\ +\ 25 \approx\ 9220CHF/year$ (≈9235 CHF when rounded})

Correct answer: Option A

Car Switching to BEV: Break-even Electricity Price

A BEV is considered with the following parameters:

- **Usage:** 20,000 km/year; consumption: 10 kWh/100 km
- **Investment:** 35,000 CHF financed over 4 years at 0.9%
- **Annual Service:** 500 CHF; **Disposal Fee:** 250 CHF (annualized over 4 years)
- Let p be the electricity price (in CHF/kWh). Determine p such that the BEV's total annual cost equals the fossil car's 9235 CHF/year.



(a) Compute the BEV's annual energy consumption.
(b) Calculate the annualized lease cost for 30,000 CHF.
(c) Write and solve the equation for p given that total annual cost equals fixed costs plus electricity cost.

A. (a) 2500 kWh/year; (b) ~8200 CHF/year; (c) p ~0.20 CHF/kWh

B. (a) 2500 kWh/year; (b) ~8400 CHF/year; (c) p ~0.00 CHF/kWh

C. (a) 2000 kWh/year; (b) ~8400 CHF/year; (c) p ~0.80 CHF/kWh

✔ D. (a) 2000 kWh/year; (b) ~8200 CHF/year; (c) p ~0.50 CHF/kWh

Car Switching to BEV: Break-even Electricity Price

1. **Step (a): Annual Energy Consumption**
   - $Energy = 20'000 \times \frac{10}{100} = 2000\ kWh/year$
2. **Step (b): Lease Payment for 30,000 CHF**

- Using the same annuity method, note that increasing the principal from 25,000 CHF to 30,000 CHF scales the lease by 1.2:
  - $6375 \frac{CHF}{year} \times 1.2 \approx 7650 \frac{CHF}{year}$

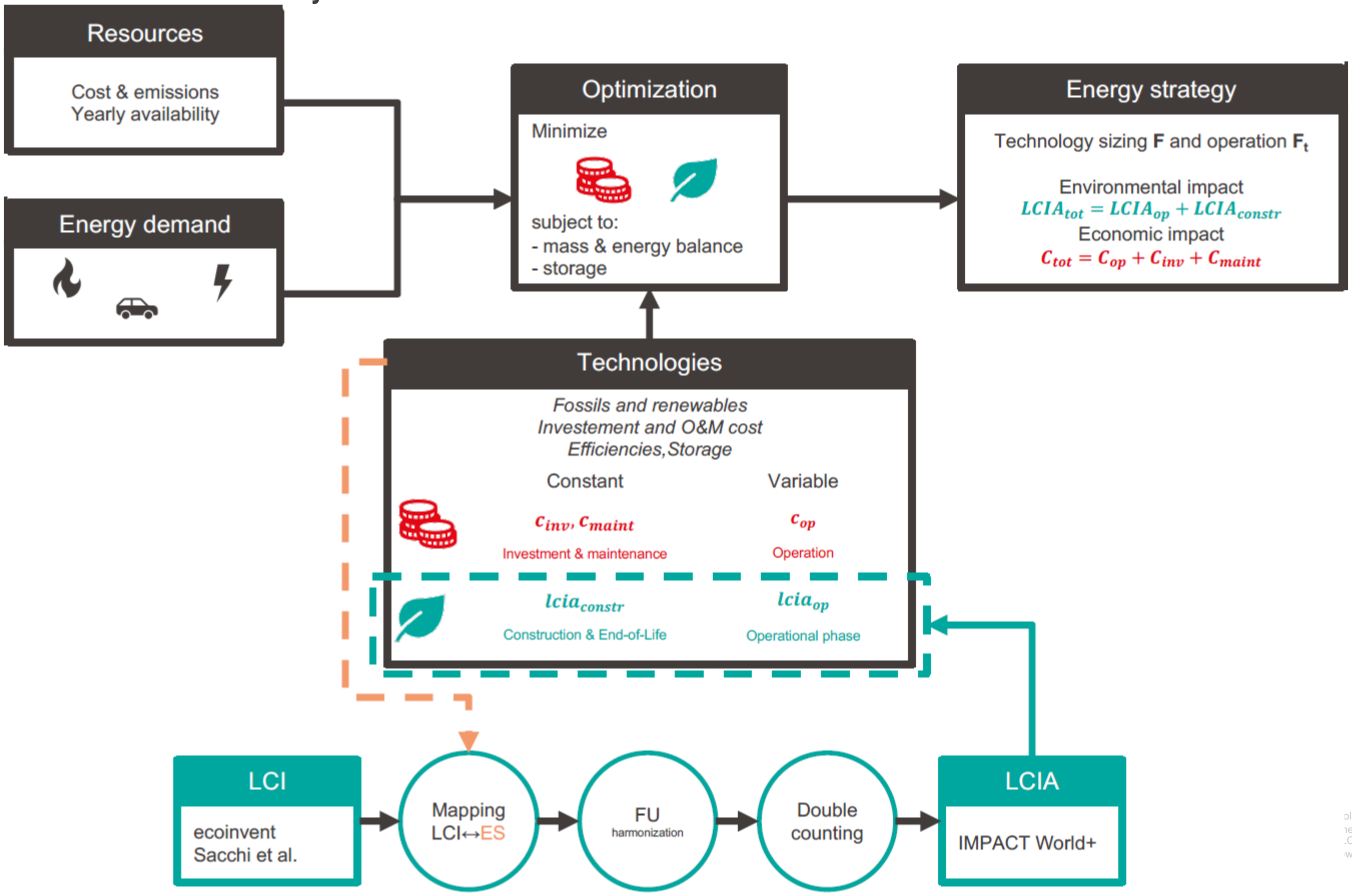
3. **Step (c): Fixed Costs**

- Fixed costs = Lease + Service + Disposal:
  - $7650 + 500 + \frac{250}{4} = 7650 + 500 + 62.5 = 8212\ CHF/year$
- Total cost equation for BEV:
  - $8212.5 + 2000p = 9235$
- Solve for p:
  - $2000p = 9235 - 8212.5 = 1022.5$
  - $p - \frac{1022.5}{2000} \approx 0.511 \frac{CHF}{kWh}$
- Thus, p ~ 0.5 CHF/kWh, indicating that the BEV will be less expensive, as long as the electricity price is ≤0.51 CHF/kWh

Correct answer: Option D

Integration of life cycle inventory

Compromises linked to sustainability



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, *2024*

Environmental indicator

DALY:
- Disability-adjusted life years
- One DALY represents the loss of the equivalent of one year of full health. DALYs for a disease or health condition are the sum of the years of life lost to due to premature mortality and the years lived with a disability due to prevalent cases of the disease or health condition in a population.

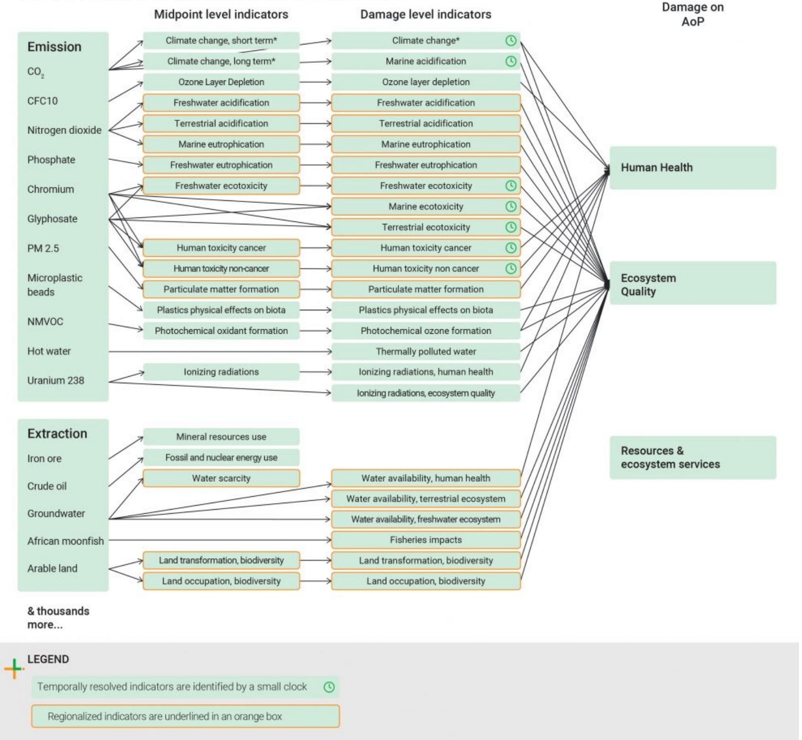
PDF m^2 year:
- Potentially Disappeared Fraction
- The unit for overall biodiversity impact using ecosystem quality and species density to describe biodiversity loss

AoP		Acronym	Indicator	Unit
Impact profile		CF	Carbon footprint	[kg · CO_2^{eq} (short)]
		FNEU	Fossil and nuclear energy use	[MJ deprived]
		REQD	Remaining Ecosystem quality damage	[DALY]
		RHHD	Remaining Human health damage	[PDF · m^2 · yr]
		WSF	Water scarcity footprint	[m^3 world – eq]
Impact categories	Human Health	CCHHL	Climate change, human health, long term	[DALY]
		CCHHS	Climate change, human health, short term	[DALY]
		HTXCL	Human toxicity cancer, long term	[DALY]
		HTXCS	Human toxicity cancer, short term	[DALY]
		HTXNCL	Human toxicity non-cancer, long term	[DALY]
		HTXNCS	Human toxicity non-cancer, short term	[DALY]
		IRHH	Ionizing radiation, human health	[DALY]
		OLD	Ozone layer depletion	[DALY]
		PMF	Particulate matter formation	[DALY]
		PCOX	Photochemical oxidant formation	[DALY]
		TTHH	Total human health	[DALY]
		WAVHH	Water availability, human health	[DALY]
	Ecosystem Quality	CCEQL	Climate change, ecosystem quality, long term	[PDF · m^2 · yr]
		CCEQS	Climate change, ecosystem quality, short term	[PDF · m^2 · yr]
		FWA	Freshwater acidification	[PDF · m^2 · yr]
		FWEXL	Freshwater ecotoxicity, long term	[PDF · m^2 · yr]
		FWEXS	Freshwater ecotoxicity, short term	[PDF · m^2 · yr]
		FWEU	Freshwater eutrophication	[PDF · m^2 · yr]
		IREQ	Ionizing radiation, ecosystem quality	[PDF · m^2 · yr]
		LOBDV	Land occupation, biodiversity	[PDF · m^2 · yr]
		LTBDV	Land transformation, biodiversity	[PDF · m^2 · yr]
		MAL	Marine acidification, long term	[PDF · m^2 · yr]
		MAS	Marine acidification, short term	[PDF · m^2 · yr]
		MEU	Marine eutrophication	[PDF · m^2 · yr]
		TRA	Terrestrial acidification	[PDF · m^2 · yr]
		TPW	Thermally polluted water	[PDF · m^2 · yr]
		TTEQ	Total ecosystem quality	[PDF · m^2 · yr]
		WAVFWES	Water availability, freshwater ecosystem	[PDF · m^2 · yr]
		WAVTES	Water availability, terrestrial ecosystem	[PDF · m^2 · yr]

LCA indicators according to IW+ integrated in ES with their respective abbreviation and unit.

IMPACT World+

v2.1 - MIDPOINT-EXPERT, METHODOLOGICAL FRAMEWORK



IMPACT World+ Framework
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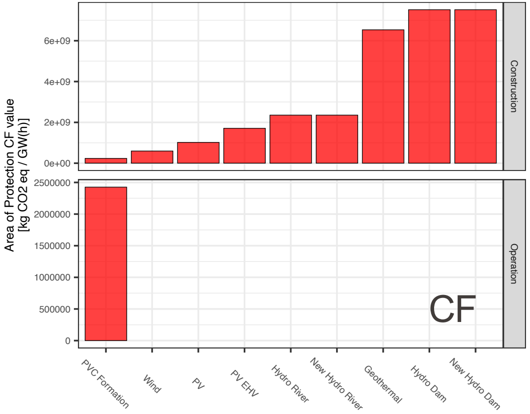
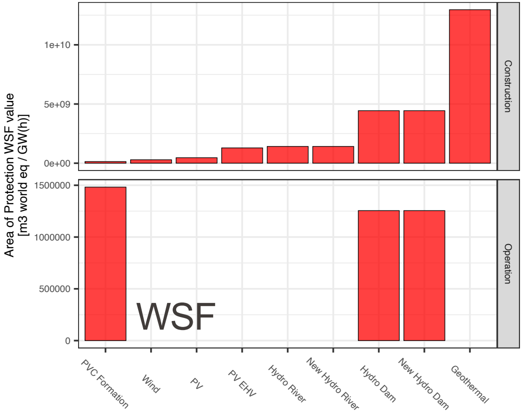
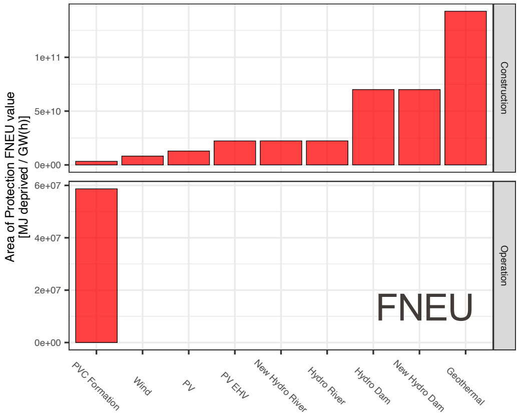
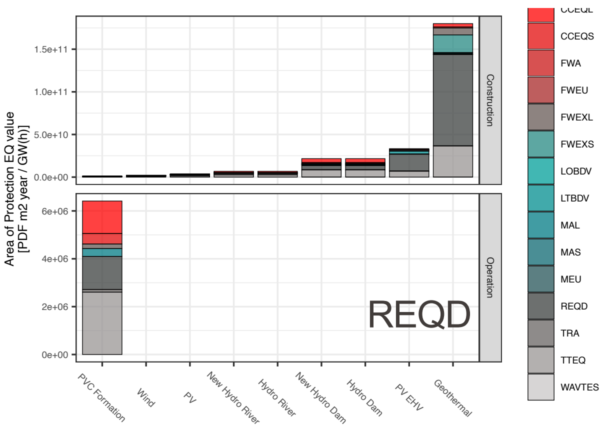
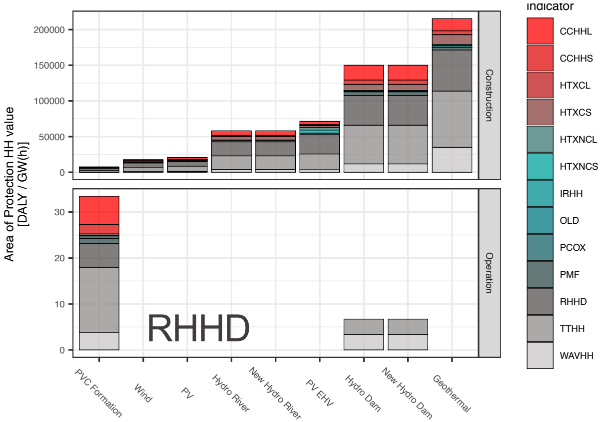
LCIA Technology impact - RE











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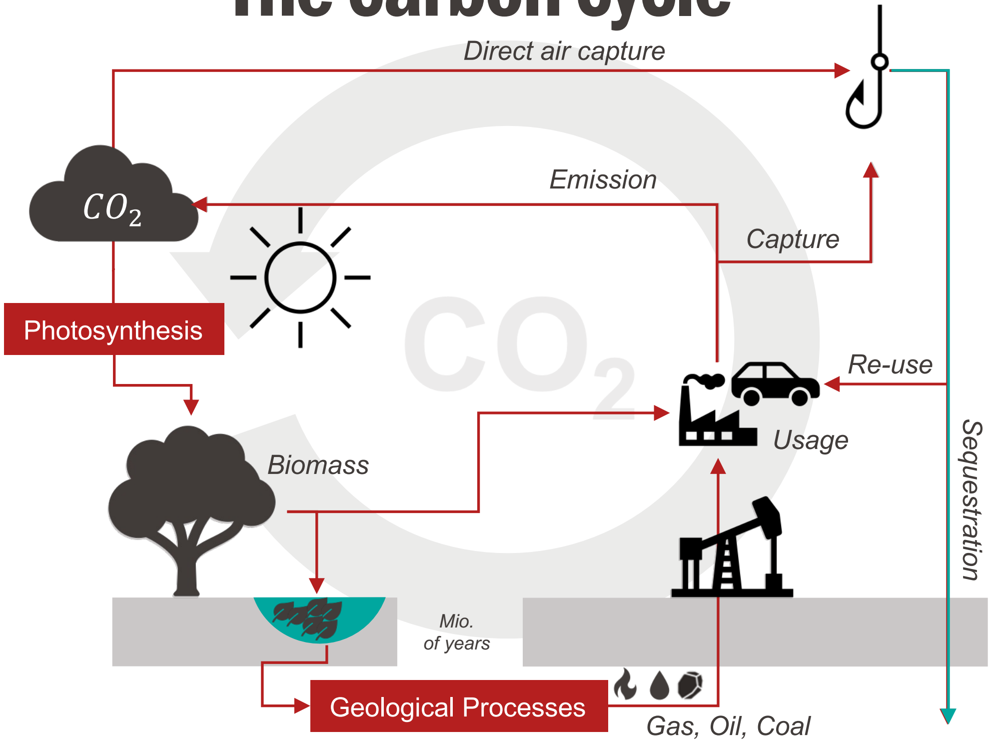
AGENDA

Carbon Cycle

The carbon cycle



- **Definition**:
  The carbon cycle in energy systems represents the movement of carbon atoms through sources, conversions, and sinks, spanning biogenic and non-biogenic origins.
- Key Components:
  - Carbon Sources:
    - **Biogenic**: Biomass (wood, wet biomass, plants).
    - **Non-biogenic**: Fossil fuels (natural gas, petroleum products, cement manufacturing emissions).
  - Carbon Sinks:
    - **Natural**: Oceans, Forests, other vegetation etc.
    - **Artificial**: Carbon capture, utilization, and storage (CCUS).
  - Intermediate Carbon Flows:
    - CO_2 emissions from energy conversion and utilization technologies.
    - CO_2 utilization for fuel and chemical synthesis.

Years → Millions of Years → Seconds → Hours/days → Years → Millenia

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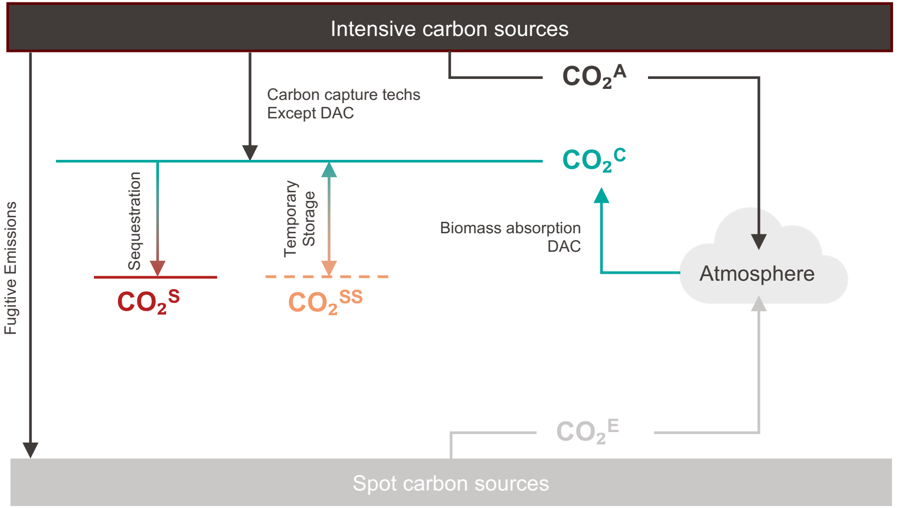
The Carbon Cycle

Modeling the Carbon Cycle in Energy Systems



- Models carbon flows as interconnected "layers" balancing inputs and outputs.
  - CO_2 Emission Layer (**CO_2^A**): From **concentrated** sources (e.g., power plants).
  - CO_2 Emission Layer (CO_2^E): From **decentralized** sources (e.g., transport).
  - CO_2 Capture Layer (**CO_2^C**): **Captured** emissions stored or utilized.
  - CO_2 Storage Layer (**CO_2^S**): **Sequestrated** (long-term)
  - CO_2 Storage Layer (**CO_2^{SS}**): **Storage** (short-term)
- Mathematical Representation:
  - Carbon Content:

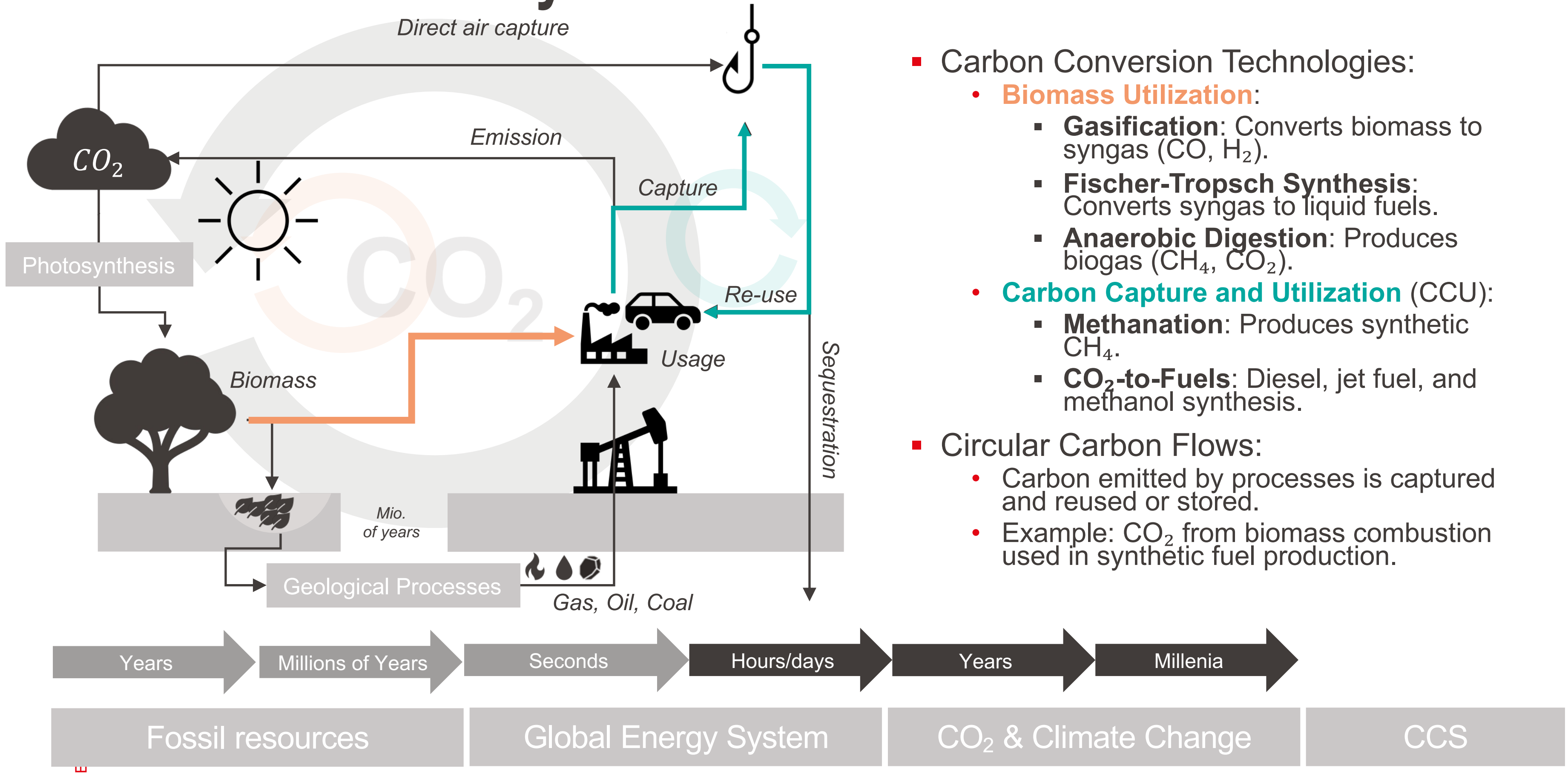
$$Carbon\ Content_r = \frac{m(C)}{m(r) \cdot LHV_r}$$

- Emission Balances:

$$Emission(t) = \sum_{j \in E, c \in C} F_t(j) \cdot \eta(j,c)$$

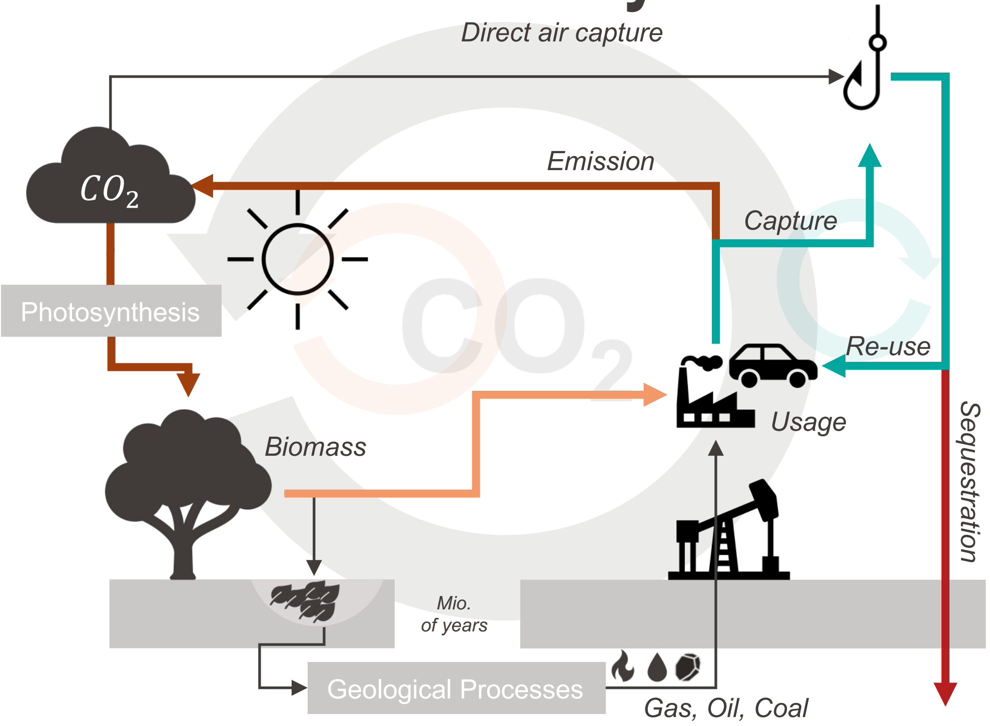
  - $F_t(j)$: Flow from technology j in period t.
  - $\eta(j,c)$: Emission factor for technology j in carbon layer c.

The Carbon Cycle - Carbon Flow and Conversion



- Carbon Conversion Technologies:
  - Biomass Utilization:
    - **Gasification**: Converts biomass to syngas (CO, H_2).
    - **Fischer-Tropsch Synthesis**: Converts syngas to liquid fuels.
    - **Anaerobic Digestion**: Produces biogas (CH_4, CO_2).
  - Carbon Capture and Utilization (CCU):
    - **Methanation**: Produces synthetic CH_4.
    - **CO_2-to-Fuels**: Diesel, jet fuel, and methanol synthesis.
- Circular Carbon Flows:
  - Carbon emitted by processes is captured and reused or stored.
  - Example: CO_2 from biomass combustion used in synthetic fuel production.

The Carbon Cycle - Carbon Sinks and Utilization



- Natural Carbon Sinks:
  - Reforestation and afforestation.
  - Biomass acting as a temporary carbon storage.
- Artificial Carbon Sinks:
  - CCS: Long-term storage in geological formations.
  - CCU:
    - Produces fuels (methane, diesel) and chemicals.
    - Reduces dependency on fossil fuels but does not eliminate emissions.
- Role of Negative Emissions:
  - Bioenergy with Carbon Capture and Sequestration, Combines biomass combustion with CCS for **net-negative emissions.**

The Carbon Cycle
Decarbonizing Energy Systems

- **Pathways**:
  - Increase renewable energy use and reduce fossil fuel dependency.
  - Maximize carbon recycling through CCU technologies.
  - Implement large-scale CCS for unavoidable emissions.
- **Challenges**:
  - Balancing economic feasibility and technological limitations.
  - Managing the complexity of interconnected carbon flows.
- **Take-home**:
  - The integration of carbon cycle modeling is essential for planning decarbonized energy systems.
  - Optimizing carbon sources, sinks, and flows ensures minimal environmental impact while meeting energy demands.

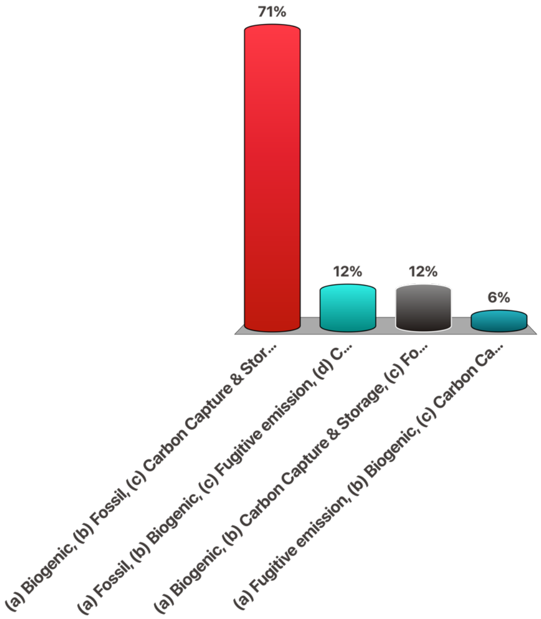
Carbon Cycle Classification

For each scenario below, select the combination that correctly classifies the carbon flow in the context of the carbon cycle:

Scenarios:

(a) CO_2 emitted from burning wood in a biomass power plant.
(b) CO_2 emitted from a natural gas power plant.
(c) CO_2 captured from an industrial facility and injected underground.
(d) Methane leaking from a natural gas pipeline.

- ✔ A. (a) Biogenic, (b) Fossil, (c) Carbon Capture & Storage, (d) Fugitive emission
- B. (a) Fossil, (b) Biogenic, (c) Fugitive emission, (d) Carbon Capture & Storage
- C. (a) Biogenic, (b) Carbon Capture & Storage, (c) Fossil, (d) Fugitive emission
- D. (a) Fugitive emission, (b) Biogenic, (c) Carbon Capture & Storage, (d) Fossil



Carbon Cycle Classification

- **(a)** Wood is a renewable, biogenic resource; thus, CO_2 from burning wood is **biogenic**.
- **(b)** Natural gas is of geological origin; its combustion releases **fossil** carbon.
- **(c)** Captured CO_2 that is injected underground is classified as **Carbon Capture & Storage (CCS)**.
- **(d)** Methane leaking from pipelines is an unintentional, uncontrolled release—i.e., a **fugitive emission**.

Correct answer: Option A (again ☺)

A G E N D A

Energy System Modeling

Carbon Cycle

The EnergyScope Framework

Optimization

Multi-Objective Optimization

The optimization framework

$$\min \quad f^{obj}(F, F_t) \qquad \text{s.t.:}$$

$$\begin{aligned} &\text{Mass and Energy Balances} \\ &\text{Resource Constraints} \\ &\text{Technology Constraints} \\ &\text{Demand Constraints} \\ &\text{Policy Constraints} \end{aligned}$$

- Objective Function f^{obj}:
  - Minimize impacts subject to constraints:
    - Energy balance
    - Resource availability
    - Technological capacities
- Optimization Outputs:
  - Technology sizing F and operation F_t
  - Energy dispatch across scenarios (e.g., future years, renewable penetration).

min Cost	min Remaining Ecosystem Quality Damage	min Remaining Human Health Damage	min Carbon Footprint	min Fossil & Nuclear Energy Use	min Water Scarcity Footprint

The optimization framework

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$$\min \quad f^{obj}(F, F_t) \qquad \text{s.t.:}$$

Mass and Energy Balances
Resource Constraints
Technology Constraints
Demand Constraints
Policy Constraints

- **Objective Function** $f^{obj} = f^{obj}_{size} + f^{obj}_{operation}$
  - Minimize impacts:
    - Cost: $f^{obj}_{cost} = C_{tot} = C^{tot}_{inv} + C^{tot}_{maint} + C^{tot}_{op}$

$$= \sum_{TEC}(C_{inv}[tec] + C_{maint}[tec]) + \sum_{RES} C_{op}[res]$$

$$= \sum_{TEC}(c_{inv}[tec] \cdot \boldsymbol{F}[tec] \cdot \tau[tec] + c_{maint}[tec] \cdot \boldsymbol{F}[tec])$$

$$+ \sum_{RES} \sum_{T}\left(c_{op}[res] \cdot \boldsymbol{F_t}[res] \cdot t_{op}[t]\right)$$

    - Environmental: $f^{obj}_{LCIA} = LCIA = LCIA^{tot}_{static} + LCIA^{tot}_{variable}$

$$= \sum_{TEC}(LCIA_{constr}[tec] + LCIA_{op}[tec]) + \sum_{RES} LCIA_{op}[res]$$

$$= \sum_{TEC}\left(lcia_{constr}[tec] \cdot \boldsymbol{F}[tec] + \sum_{T}\left(lcia_{op}[tec] \cdot \boldsymbol{F_t}[tec] \cdot t_{op}[t]\right)\right)$$

$$+ \sum_{RES} \sum_{T}\left(lcia_{op}[res] \cdot \boldsymbol{F_t}[res] \cdot t_{op}[t]\right)$$

- Optimization Outputs:
  - Technology sizing $\boldsymbol{F}$ and operation $\boldsymbol{F_t}$

min Cost	min Remaining Ecosystem Quality Damage	min Remaining Human Health Damage	min Carbon Footprint	min Fossil & Nuclear Energy Use	min Water Scarcity Footprint

The optimization framework

$$\min \quad f^{obj}(F, F_t) \qquad \text{s.t.:}$$

Mass and Energy Balances
Resource Constraints
Technology Constraints
Demand Constraints
Policy Constraints

- Energy & Mass balance in every period t :

  End-Uses: $EU(l,t)$

$$= \sum_{tec}\left(\boldsymbol{F_t}(tec,t)\cdot\eta(tec,l)\right)$$
$$+\sum_{res}\left(\boldsymbol{F_t^+}(res,t)-\boldsymbol{F_t^-}(res,t)\right)$$
$$+\sum_{sto}\left(\boldsymbol{F_t^+}(sto,l,t)-\boldsymbol{F_t^-}(sto,l,t)\right)$$
$$-F_t^{Loss}(l,t)$$

The optimization framework

$$\min \quad f^{obj}(F, F_t) \qquad \text{s.t.:}$$

Mass and Energy Balances
Resource Constraints
Technology Constraints
Demand Constraints
Policy Constraints

- Resource Constraints

$$\sum_t \left(\boldsymbol{F_t}(res, t) \cdot t_{op}(t) \right) \leq avail(res)$$

- Technology Constraints
  - Sizing:

$$f_{min}(tec) \leq \boldsymbol{F}(tec) \leq f_{max}(tec)$$

  - Use:

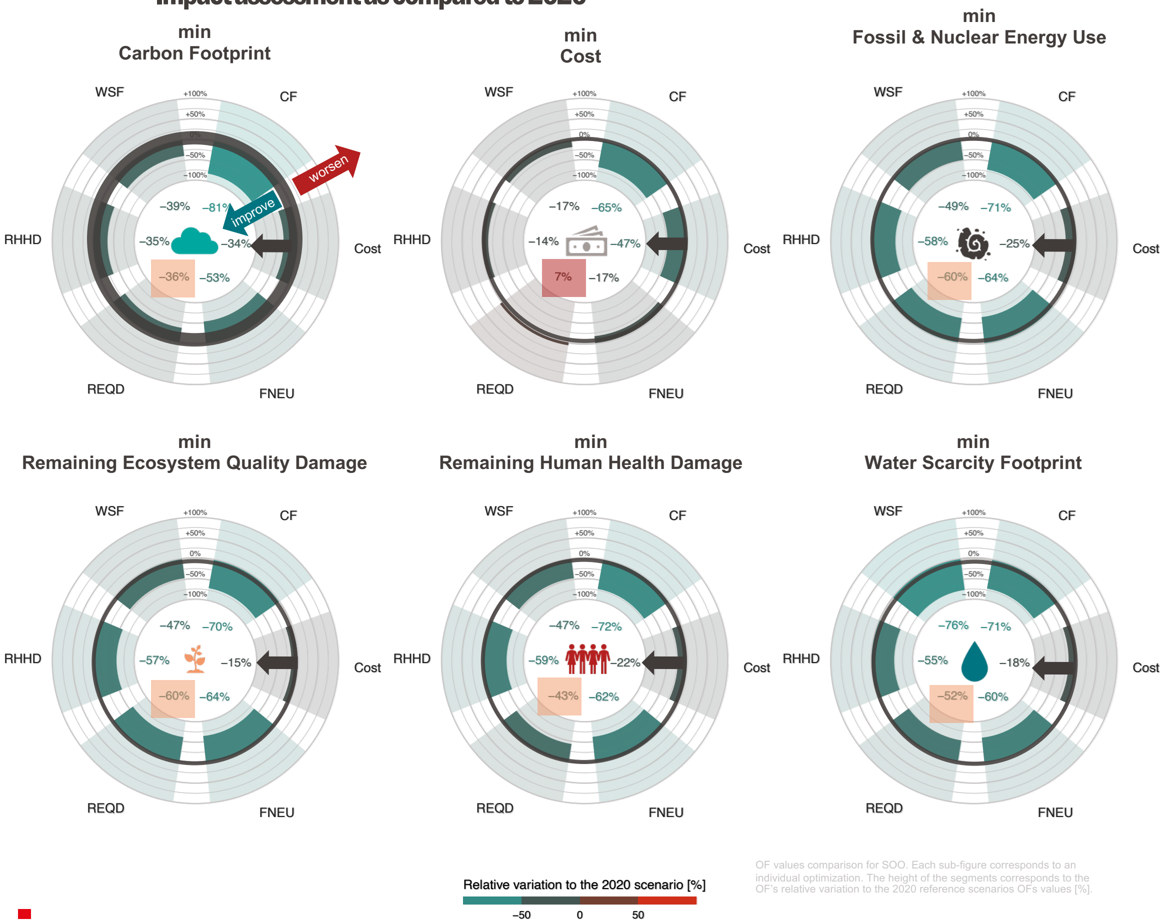
$$\boldsymbol{F_t}(tec, t) \leq \boldsymbol{F}(tec) \cdot c_{p,t}(t)$$

  - Annual Capacity:

$$\sum_t \left(\boldsymbol{F_t}(tec, t) \cdot t_{op}(t) \right) \leq \boldsymbol{F}(tec) \cdot c_p \sum_t t_{op}(t)$$

Go green: minimizing Impacts

Impact assessment as compared to 2020



OF values comparison for SOO. Each sub-figure corresponds to an individual optimization. The height of the segments corresponds to the OF's relative variation to the 2020 reference scenarios OFs values [%].

- Optimizing environomic indicators individually
- Tracking effect of other indicators in comparison to **2020**
- Minimizing any environmental indicator leads to **cost-reduction**
- Single-Objective Optimization leads to burden-shifting

→ Impact Trade-offs?

CF:	Carbon Footprint
FNEU:	Fossil & Nuclear Energy Use
REQD:	Remaining Ecosystem Quality Damage
RHHD:	Remaining Human Healt Damage
WSF:	Water Scarcity Footprint

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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, *Author's Accepted Manuscript*

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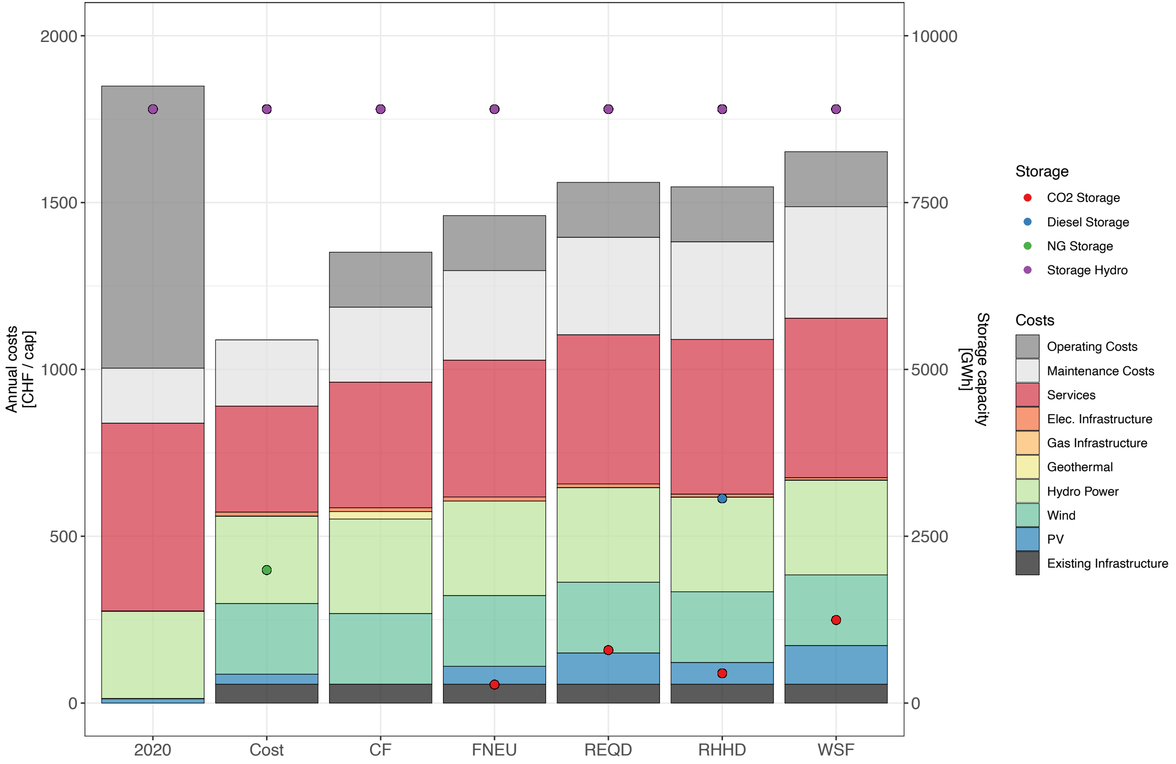
Single-Objective Optimization
Energy System Configurations



Overall cost composition of energy systems for single-objective optimizations. The secondary axis highlights installed storage capacity. The 2020 scenario represents the current Swiss energy system, and the other six represent hypothetical scenarios for an energy-independent Switzerland in 2020 with single objective optimization.

- Current System (2020 Reference Case):
  - High operational costs due to significant reliance on imported fossil fuels.
- Hypothetical Energy-Independent Scenarios:
  - Fully self-sustained systems utilizing only local energy resources.
  - Diverse optimization objectives lead to variations in system configurations.
- Renewable Energy Deployment:
  - Maximum utilization of wind and hydropower resources.
  - Photovoltaic (PV) capacity ranges from 7 GW to 20 GW, except in the CF minimization scenario, which favors geothermal power (3.5 GW).
- Energy Storage Capacity:
  - Significant installation to balance renewable intermittency.
  - Capacity details highlighted on the secondary axis of the figure.
- Biomass Utilization:
  - Maximized in most scenarios except for cost minimization.
  - Highlights local resource reliance.

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AGENDA

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Multi-Objective Optimization
Pareto-Front – 2 Dimensions

The Pareto front represents the set of all non-dominated solutions in a multi-objective optimization problem, where no objective can be improved without worsening at least one other objective.

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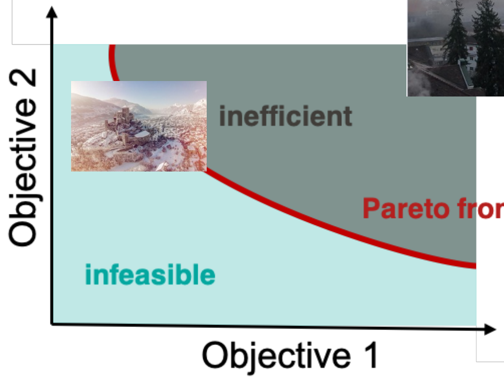

Choosing your holiday destination:
- Objective 1: Sunny Beach Paradise
- Objective 2: Alpine Mountain Retreat
- Infeasible: "*Zermatt sur mer*" (?)
- Inefficient: Foggy Lausanne
- Compromise: Sion: Sunny, alpine, beautiful, …

Methods to derive the Pareto-Front

- **Epsilon-Method**
  Optimize one objective while treating the other objectives as constraints bounded by epsilon values.

$$\min f_1^{obj}(F, F_t)$$
$$s.t. \quad f_2^{obj} < \epsilon$$

- **Weighted Sum Method**
  Combine multiple objectives into a single objective using weighted coefficients.

$$\min f_1^{obj}(F, F_t) \cdot \omega_1 + f_2^{obj}(F, F_t) \cdot \omega_2$$
$$s.t. \quad \omega_1 + \omega_2 = 1, \omega_{1,2} \geq 0$$

! Issues with different orders of magnitude of f_i^{obj}

- **Weighted Epsilon-Method**
  Define $f_2^{min,max}$ and parametrize using weighted epsilon values

$$\min f_1^{obj}(F, F_t)$$
$$s.t. \quad f_2^{obj} \leq \omega_2 \cdot f_2^{max} + (1 - \omega_2) \cdot f_2^{min}, \omega_2 \geq 0$$

When planning your holidays, finding the perfect balance between sunshine and snow activities can be a tricky optimization! Sion sits right on the Pareto front, offering the best of both worlds

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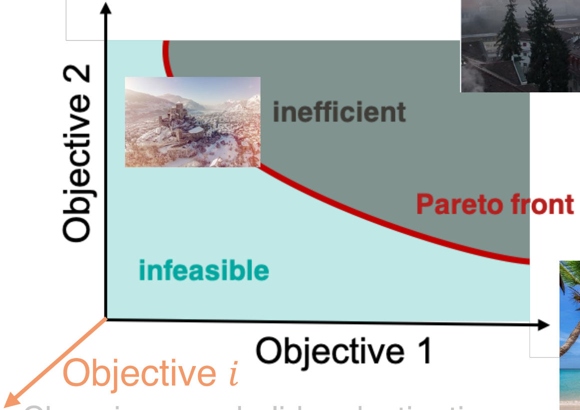
Multi-Objective Optimization

N-Dimensions

The Pareto front represents the set of all non-dominated solutions in a multi-objective optimization problem, where no objective can be improved without worsening at least one other objective.



Choosing your holiday destination:

- Objective 1: Sunny Beach Paradise
- Objective 2: Alpine Mountain Retreat
- Objective i: I want to minimize my CO_2 footprint
- Infeasible: "*Zermatt sur mer*" (?)
- Inefficient: Foggy Lausanne
- Compromise: Sion: Sunny, alpine, beautiful, …

Methods to derive the Pareto-Front

- **Epsilon-Method**
  Optimize one objective while treating the other objectives as constraints bounded by epsilon values.

$$\min f_i^{obj}(F, F_t)$$
$$s.t. \quad f_j^{obj} < \epsilon_j$$

- **Weighted Sum Method**
  Combine multiple objectives into a single objective using weighted coefficients.

$$\min \sum_i f_i^{obj} \cdot \omega_i$$
$$s.t. \quad \sum_i \omega_i = 1, \omega_i \geq 0$$

! Issues with different orders of magnitude of f_i^{obj}

- **Weighted Epsilon-Method**
  Define $f_i^{min,max}$ and parametrize using weighted epsilon values

$$\min f_j^{obj}(F, F_t)$$
$$s.t. \quad f_i^{obj} \leq \omega_i \cdot f_i^{max} + (1 - \omega_i) \cdot f_i^{min}, \omega_i \geq 0$$

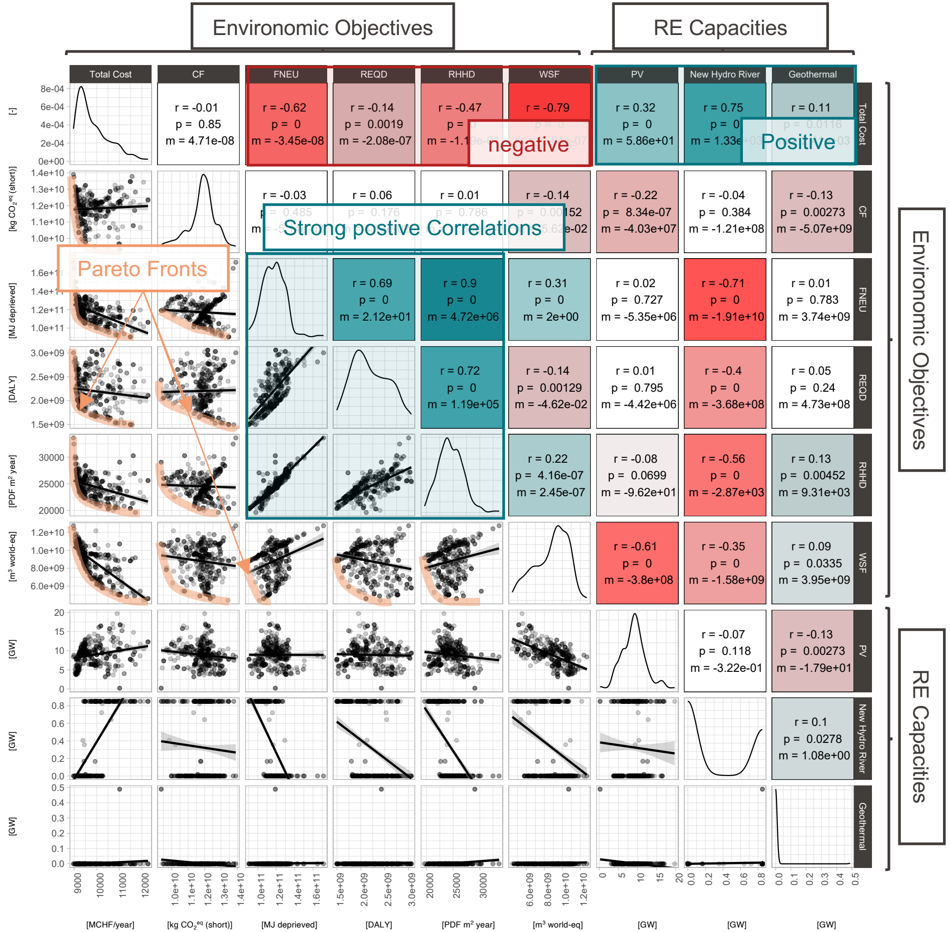
When planning your holidays, finding the perfect balance between sunshine and snow activities can be a tricky optimization! Sion sits right on the Pareto front, offering the best of both worlds

Burden shifting?

Multi-parametric optimization of environomic indicators

$$\min_{\mathbf{F},\mathbf{F_t}} \mathbf{C_{tot}}$$
$$\text{s.t.} \quad \mathbf{f_{obj}}(i) \le \omega(i)\cdot \mathrm{f_{obj}}^{\max}(l) + (1-\omega(i))\cdot \mathrm{f_{obj}}^{\min}(l)$$
$$\forall \quad i \in \mathcal{OF} = \mathcal{C} \cup \mathcal{LCIA} - \mathcal{I}$$
$$\mathbf{F}(i), \mathbf{F_t}(i): \quad f((\mathbf{F}(i), \mathbf{F_t}(i)), \omega(i))$$
$$\text{s.t.} \quad \omega(i) = P(\tilde{\omega}, \mathrm{U}(0,1))$$

Jonas Schnidrig

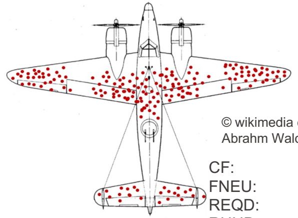


Pearson correlation coefficient matrix based on the MOO. The upper triangle depicts the correlation factor *r* with the color gradient and the significance *p* with the transparency. Red indicates a negative correlation, while green indicates a positive correlation. The transparency is set such as $p \le 0.05$ are not significant under the initial hypothesis of not correlating, thus leading to complete transparency over the latter value. Furthermore, the trend-line *m* gradient is expressed, indicating the linear dependency between the OF and the installed capacities.
The diagonal depicts the distribution of the appearance of the individual variables. The lower triangle represents the observation distribution with the corresponding trend line and 95 % confidence interval. Each point corresponds to one distinct configuration. The Pareto-front between the OF can be observed.

- Pareto-Optimal Solution Space
- Environmental Correlation
  - RHHD & FNEU & REQD
  - CF no significant correlations
- Economic:
  - Negative correlation wrt sustainability
  - Positive correlation wrt technologies

! Correlations in the optimal solution space

- Wind always deployed at maximum
- Sub-optimal configurations & technologies not represented



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Abrahm Wald Problem

CF:	Carbon Footprint
FNEU:	Fossil & Nuclear Energy Use
REQD:	Remaining Ecosystem Quality Damage
RHHD:	Remaining Human Healt Damage
WSF:	Water Scarcity Footprint

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Conclusion

How can LCA indicators be integrated into energy system models to optimize both environmental and economic outcomes for the energy transition?

- **Integration of LCA Indicators**
  - Essential for balancing economic efficiency with environmental sustainability
  - Environmental optimization = -15% to -33% costs compared 2020
- **Multi-Parametric Optimization for generating configurations**
  - Reveals positive correlation between economic and environmental objectives
  - Sustainable MOO solution space = renewable energies
- **Burden shifting**
  - Economic optimization efficiency reduces Carbon Footprint by 63% compared to 2020
  - but shifts burdens to other environmental areas Water Scarcity, Fossil & Nuclear Energy use, due to the construction of technologies
- **Focus on Environomic Indicators**
  - Tracking potential burden shifting
  - Quantifies benefits and burden associated to different dimensions of sustainability

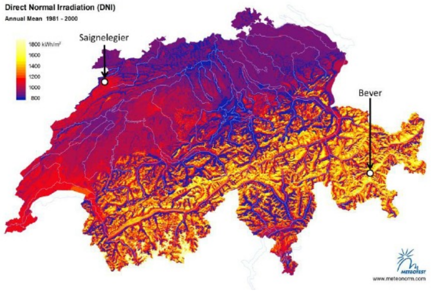
- **Limitations**
  - Static LCA based on historic activities
  - Not considering prospective LCA

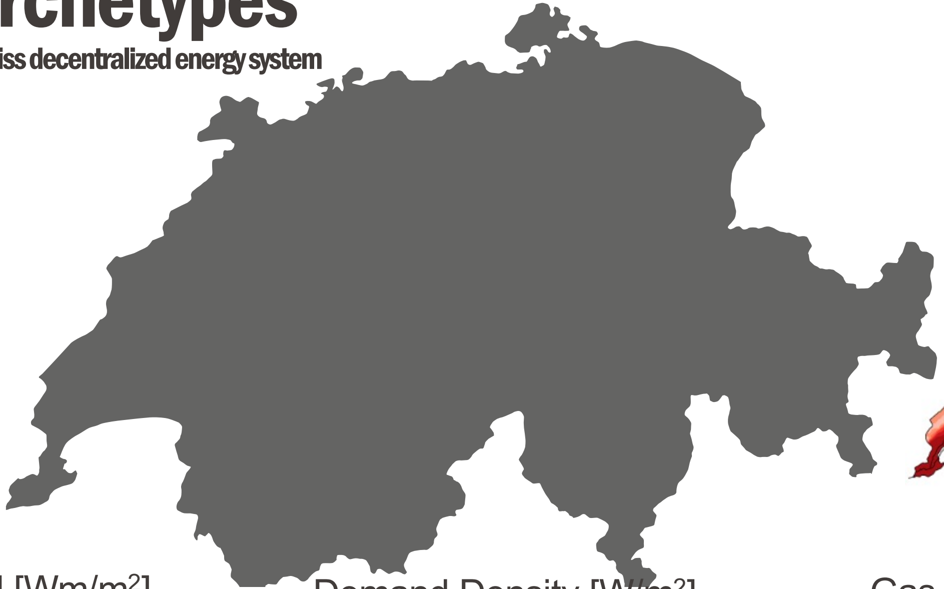
A G E N D A

District archetypes

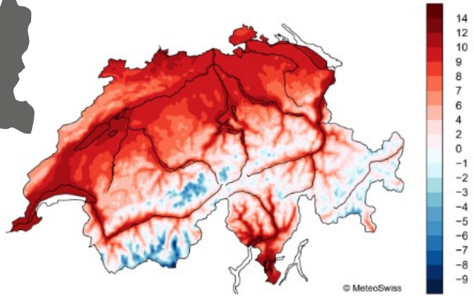
How to characterize the Swiss decentralized energy system

Irradiance [W/m²]

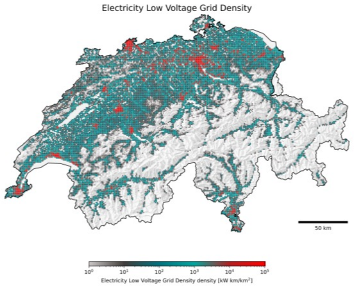




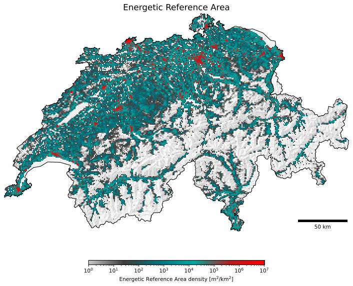
Temperature [°C]



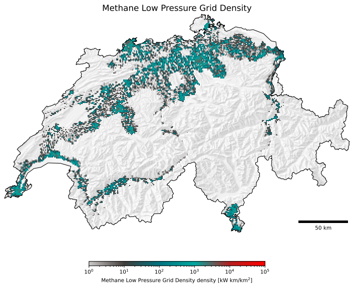
Electric grid [Wm/m²]



Demand Density [W/m²]



Gas grid [Wm/m²]



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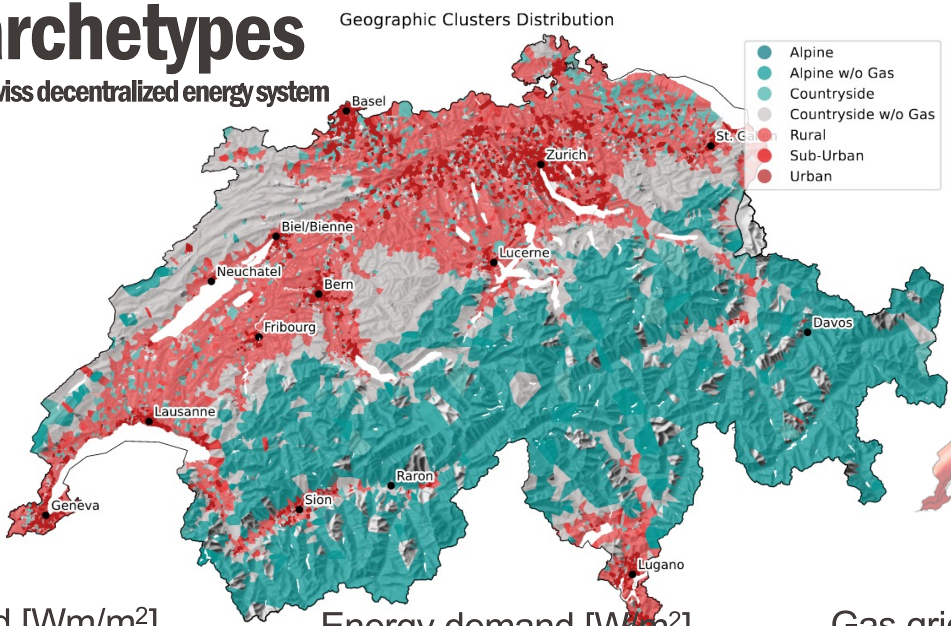
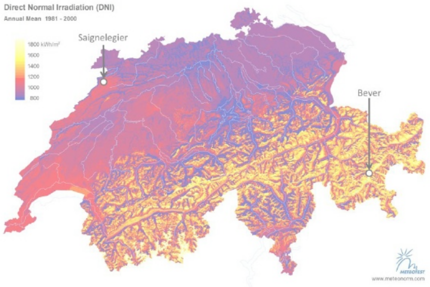
EPFL

District archetypes

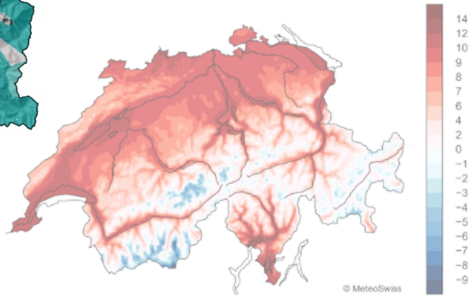
How to characterize the Swiss decentralized energy system



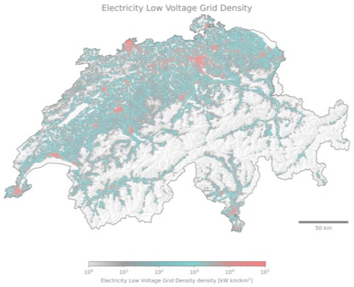
Irradiance [W/m²]



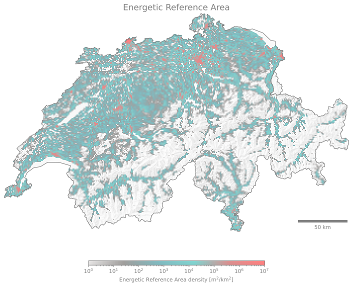
Temperature [°C]



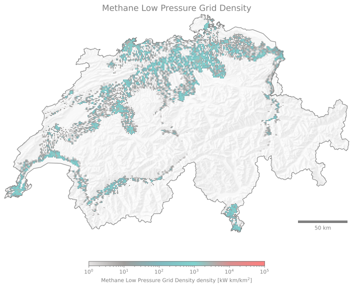
Electric grid [Wm/m²]



Energy demand [W/m²]



Gas grid [Wm/m²]



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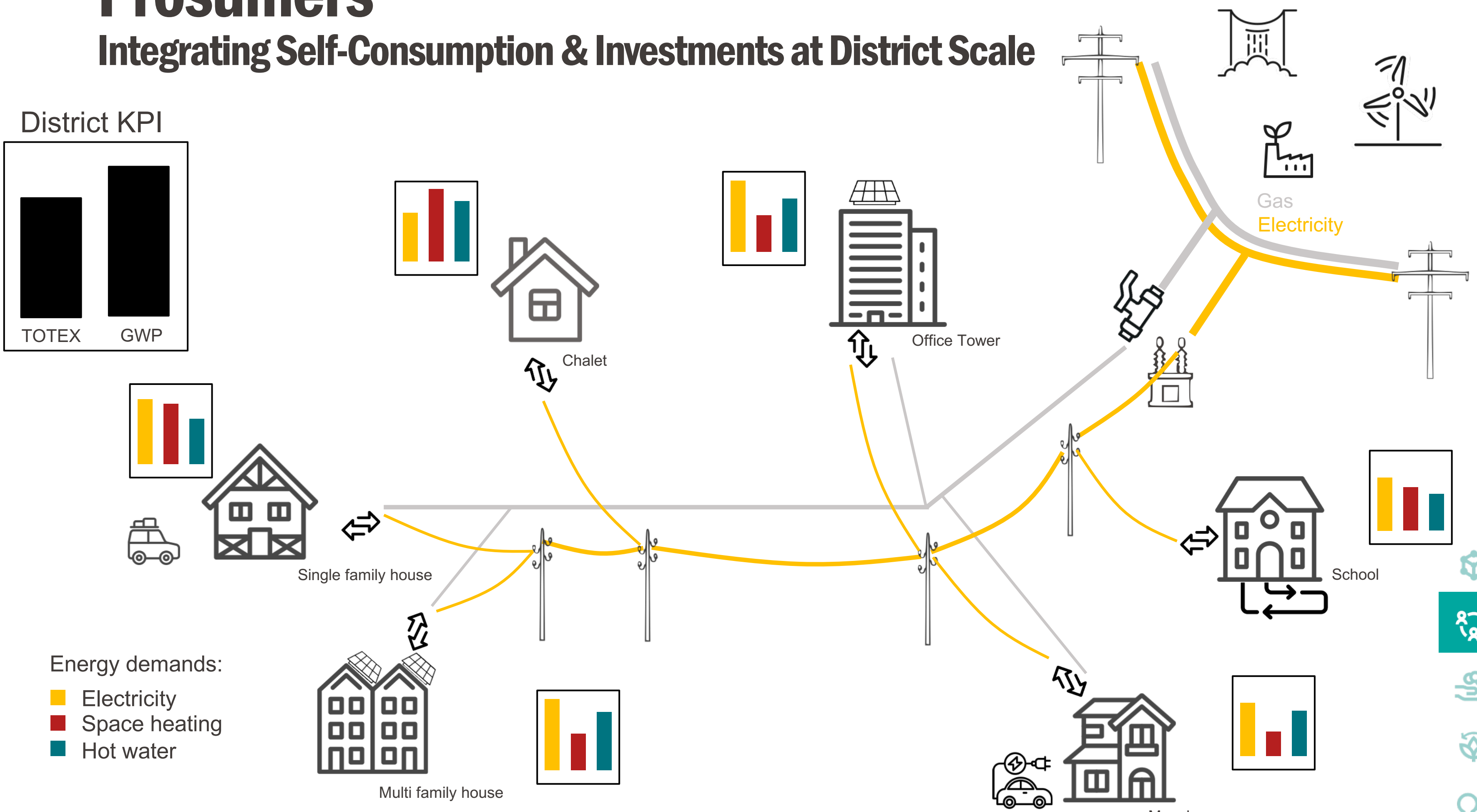
Prosumers

Integrating Self-Consumption & Investments at District Scale

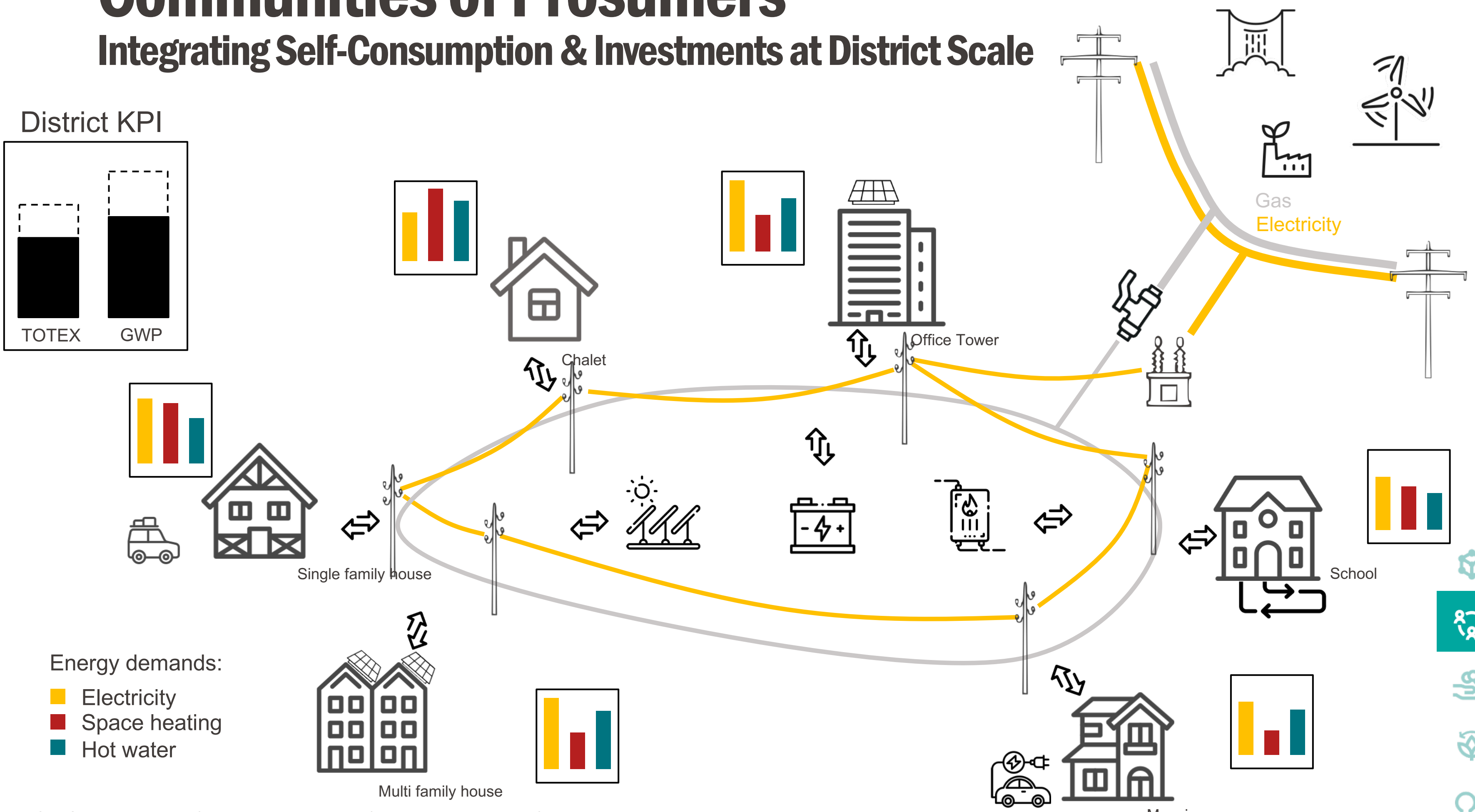


Adapted from Chuat 2023, *Impact of renewable energy hubs configurations on the national infrastructure,* Master Project EPFL

EPFL

Communities of Prosumers

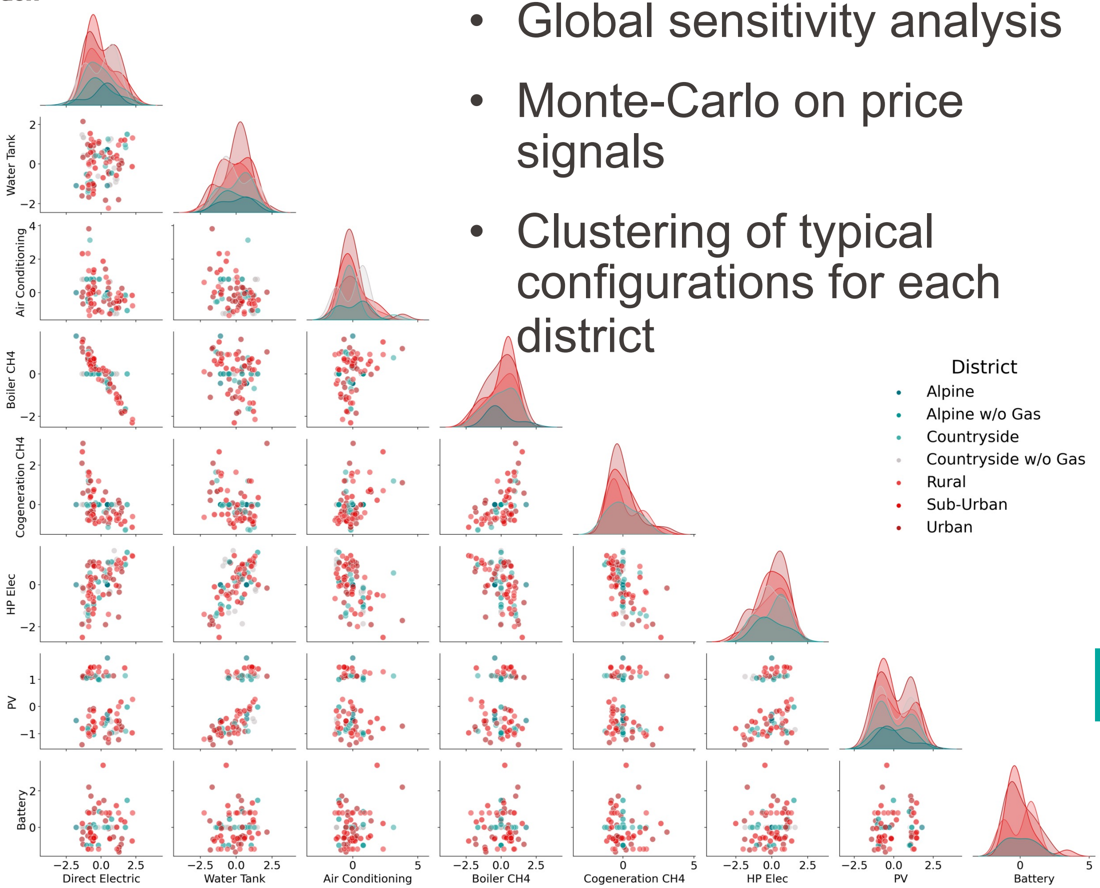
Integrating Self-Consumption & Investments at District Scale



Adapted from Chuat 2023, *Impact of renewable energy hubs configurations on the national infrastructure,* Master Project EPFL

District energy system archetypes

Generating configurations by parametric optimization



- Global sensitivity analysis
- Monte-Carlo on price signals
- Clustering of typical configurations for each district

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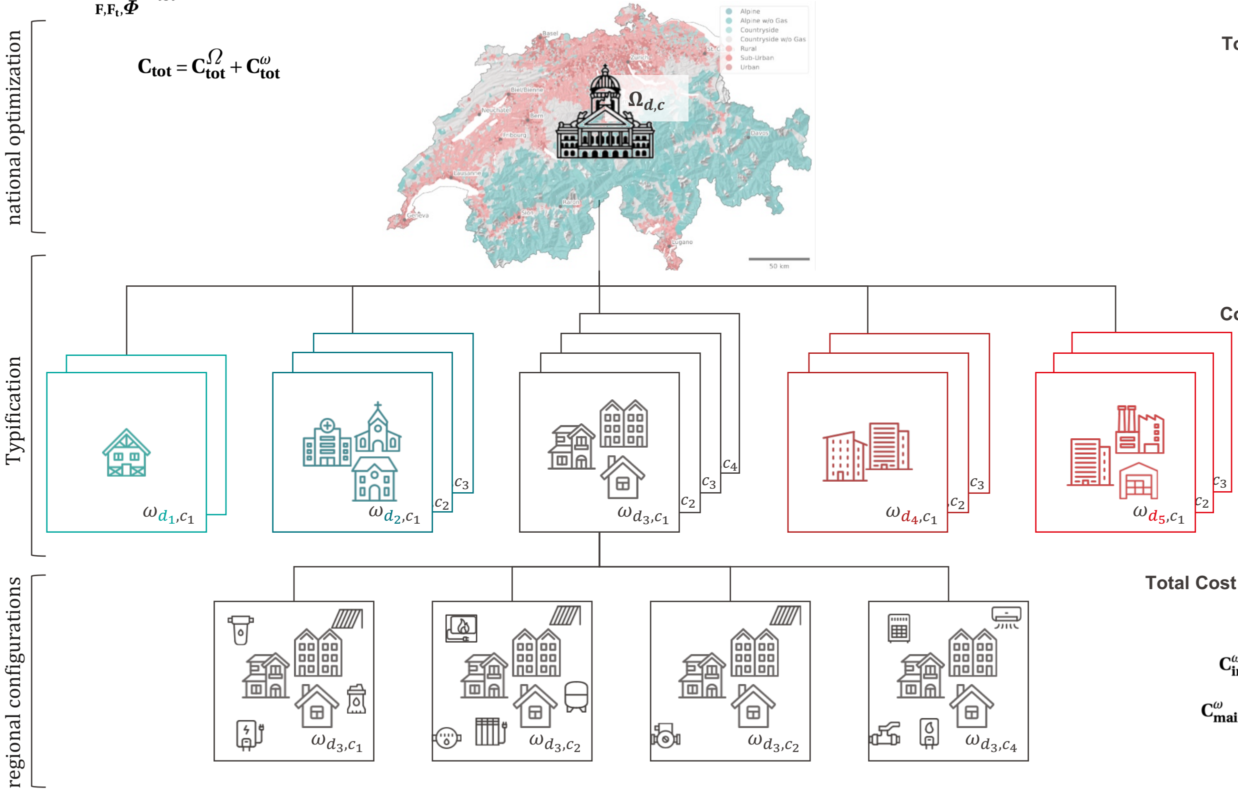
Linking national and district model

Selecting regional optimal configurations from the national point of view

Objective Function

$$\min_{\mathbf{F},\mathbf{F_t},\boldsymbol{\Phi}} \mathbf{C_{tot}} \quad \text{s.t.}$$

$$\mathbf{C_{tot}} = \mathbf{C}^{\Omega}_{\mathbf{tot}} + \mathbf{C}^{\omega}_{\mathbf{tot}}$$



Total Cost Centralized System

$$\mathbf{C}^{\Omega}_{\mathbf{tot}} = \mathbf{C}^{\Omega}_{\mathbf{op}} + \mathbf{C}^{\Omega}_{\mathbf{inv}} + \mathbf{C}^{\Omega}_{\mathbf{maint}}$$

$$\mathbf{C}^{\Omega}_{\mathbf{op}} = \sum_{res}\sum_{t} c_{op}(res,t) \cdot \mathbf{F_t}(res,t) \cdot t_{op}(t)$$

$$\mathbf{C}^{\Omega}_{\mathbf{inv}} = \sum_{tec} c_{inv}(tec) \cdot (\mathbf{F}(tec) - f^{\Omega}_{\exists}(tec^*))$$

$$\mathbf{C}^{\Omega}_{\mathbf{maint}} = \sum_{tec} c_{maint}(tec) \cdot \mathbf{F}(tec)$$

Configuration Selection

$$\sum_{c} \boldsymbol{\Phi}(c,d) = 1, \quad 0 \le \boldsymbol{\Phi}(c,d) \le 1$$

Energy Balance

$$\mathbf{EU}(l,t) = \sum_{tec} \mathbf{F_t}(tec,t) \cdot \eta(tec,l) - \mathbf{F_t^{Loss}}(l,t) + \sum_{sto} \mathbf{F_t^{+}}(sto,l,t) - \mathbf{F_t^{-}}(sto,l,t) + \sum_{d} \mathbf{F_t^{\omega+}}(d,l,t) - \mathbf{F_t^{\omega-}}(d,l,t)$$

Total Cost Districts

$$\mathbf{C}^{\omega}_{\mathbf{tot}} = \sum_{d} (\mathbf{C}^{\omega}_{\mathbf{inv}}(d) + \mathbf{C}^{\omega}_{\mathbf{maint}}(d))$$

$$\mathbf{C}^{\omega}_{\mathbf{inv}}(d) = \sum_{tec}\sum_{c} (c_{inv}(tec) \cdot f^{\omega}(tec,c,d) \cdot \boldsymbol{\Phi}(c,d))$$

$$\mathbf{C}^{\omega}_{\mathbf{maint}}(d) = \sum_{tec}\sum_{c} (c_{maint}(tec) \cdot f^{\omega}(tec,c,d) \cdot \boldsymbol{\Phi}(c,d))$$

$$\forall \quad c \in \mathcal{S}, d \in \mathcal{D}, t \in \mathcal{P}, \quad tec \in \mathcal{T}, tec^* \in \mathcal{G}, \quad res \in \mathcal{R}, sto \in \mathcal{T} - \mathcal{S}, l \in \mathcal{L}$$

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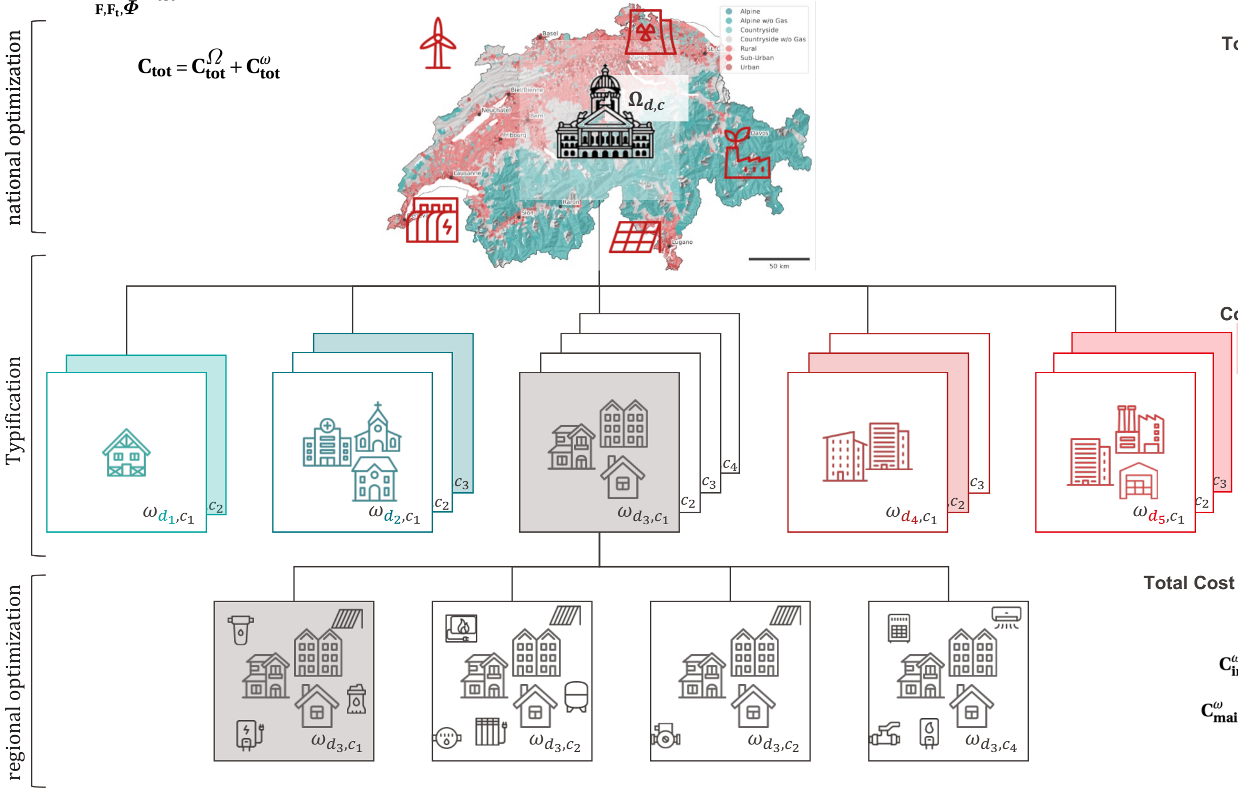
Linking national and district model

Selecting regional optimal configurations from the national point of view

Objective Function

$$\min_{\mathbf{F},\mathbf{F_t},\boldsymbol{\Phi}} \mathbf{C_{tot}} \quad \text{s.t.}$$



Total Cost Centralized System

$$\mathbf{C^{\Omega}_{tot}} = \mathbf{C^{\Omega}_{op}} + \mathbf{C^{\Omega}_{inv}} + \mathbf{C^{\Omega}_{maint}}$$

$$\mathbf{C^{\Omega}_{op}} = \sum_{res}\sum_{t} \mathrm{c_{op}}(res,t)\cdot \mathbf{F_t}(res,t)\cdot \mathrm{t_{op}}(t)$$

$$\mathbf{C^{\Omega}_{inv}} = \sum_{tec} \mathrm{c_{inv}}(tec)\cdot(\mathbf{F}(tec) - \mathrm{f}^{\Omega}_{\exists}(tec^*))$$

$$\mathbf{C^{\Omega}_{maint}} = \sum_{tec} \mathrm{c_{maint}}(tec)\cdot \mathbf{F}(tec)$$

Configuration Selection

$$\sum_{c} \boldsymbol{\Phi}(c,d) = 1, \quad 0 \le \boldsymbol{\Phi}(c,d) \le 1$$

Energy Balance

$$\mathbf{EU}(l,t) = \sum_{tec} \mathbf{F_t}(tec,t)\cdot \eta(tec,l) - \mathbf{F_t^{Loss}}(l,t) + \sum_{sto} \mathbf{F_t^{+}}(sto,l,t) - \mathbf{F_t^{-}}(sto,l,t) + \sum_{d} \mathbf{F_t^{\omega+}}(d,l,t) - \mathbf{F_t^{\omega-}}(d,l,t)$$

Total Cost Districts

$$\mathbf{C^{\omega}_{tot}} = \sum_{d}(\mathbf{C^{\omega}_{inv}}(d) + \mathbf{C^{\omega}_{maint}}(d))$$

$$\mathbf{C^{\omega}_{inv}}(d) = \sum_{tec}\sum_{c}(\mathrm{c_{inv}}(tec)\cdot \mathrm{f}^{\omega}(tec,c,d)\cdot \boldsymbol{\Phi}(c,d))$$

$$\mathbf{C^{\omega}_{maint}}(d) = \sum_{tec}\sum_{c}(\mathrm{c_{maint}}(tec)\cdot \mathrm{f}^{\omega}(tec,c,d)\cdot \boldsymbol{\Phi}(c,d))$$

$$\forall \quad c \in \mathcal{S}, d \in \mathcal{D}, t \in \mathcal{P}, \; tec \in \mathcal{T}, tec^* \in \mathcal{G}, \; res \in \mathcal{R}, sto \in \mathcal{T} - \mathcal{S}, l \in \mathcal{L}$$

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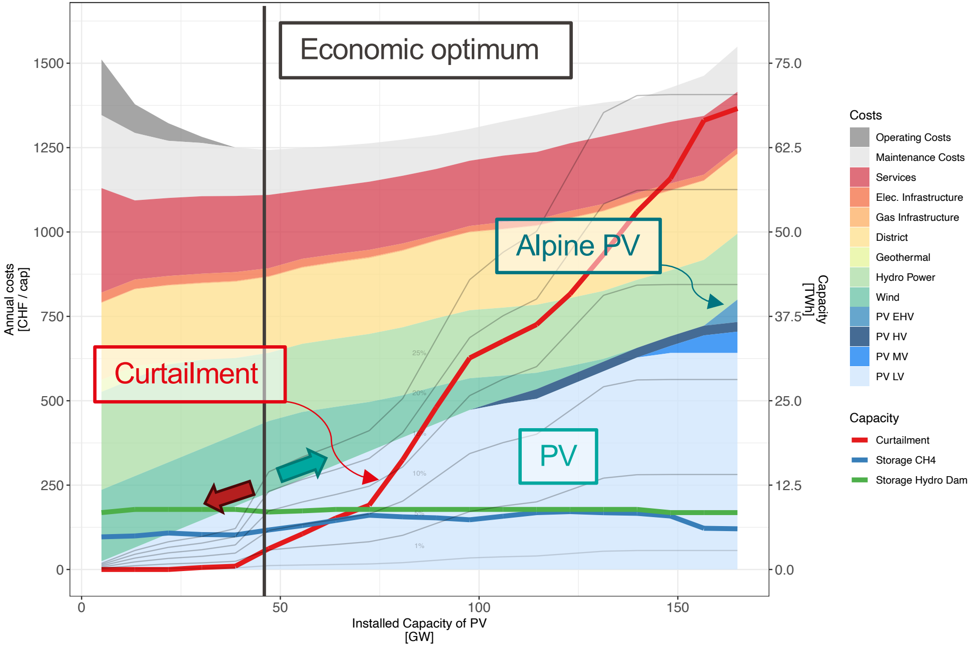
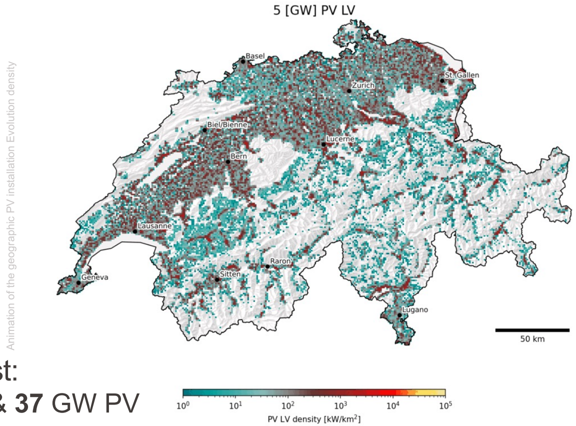
Wind-PV tradeoff *& self-consumption*

The transition towards a decentralized system



Evolution of energy system costs composition and storage capacities of the Swiss energy system



- Minimum Cost:
  20 GW Wind & **37** GW PV
  - PV: Limitation by the LV grid but more (37 GW)
  - Wind: installation to its maximum potential (20 GW)
- PV ↘
  - Wind at maximum
  - Compensation by biomass resources
    0-15% biomass potential
  - Methane storage via power-to-methane (4.3-6.1 TWh)
- PV ↗
  - Wind reduction
  - Seasonal dephasing
  - Methane storage via power-to-methane (6.1-8.8 TWh)

PV installation parametrization.
The transparent lines represent the annual PV-LV production fractions, allowing us to compare them with the curtailment depending on the installed PV capacity. The case study represents the economic optimization of a neutral (no net emission) and independent (no import) Swiss energy system in 2050 for a population of 10 Million.

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What about the grid?

PV deployment and grid reinforcement in the transition towards a decentralized system

Urban areas:

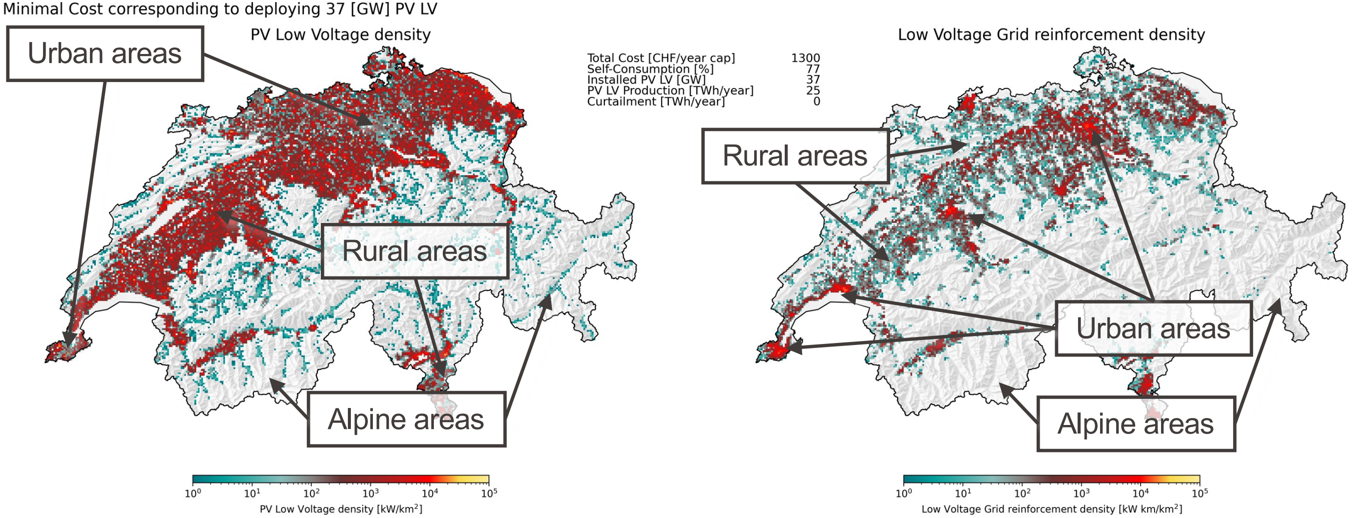
- Limited PV deployment
  50-250 kW/km^2
- Reinforcement due to electrification of heating sector
  5-21 MW km / km^2

Rural areas:

- High PV deployment
  1-50 MW/km^2
- Self-consumption & Export to urban
- Low reinforcement due to lower energy demands
  0-0.5 MW km / km^2

Alpine areas:

- PV deployment to maximise self-consumption
  15-100 kW km / km^2
- No export
- No reinforcements needed



Geographical deployment of LV PV and respective grid reinforcement in CH 2050.
Case study of the economic optimization of a neutral (no net emissions) and independent (no imports) Swiss energy system in 2050.
Cost minimization

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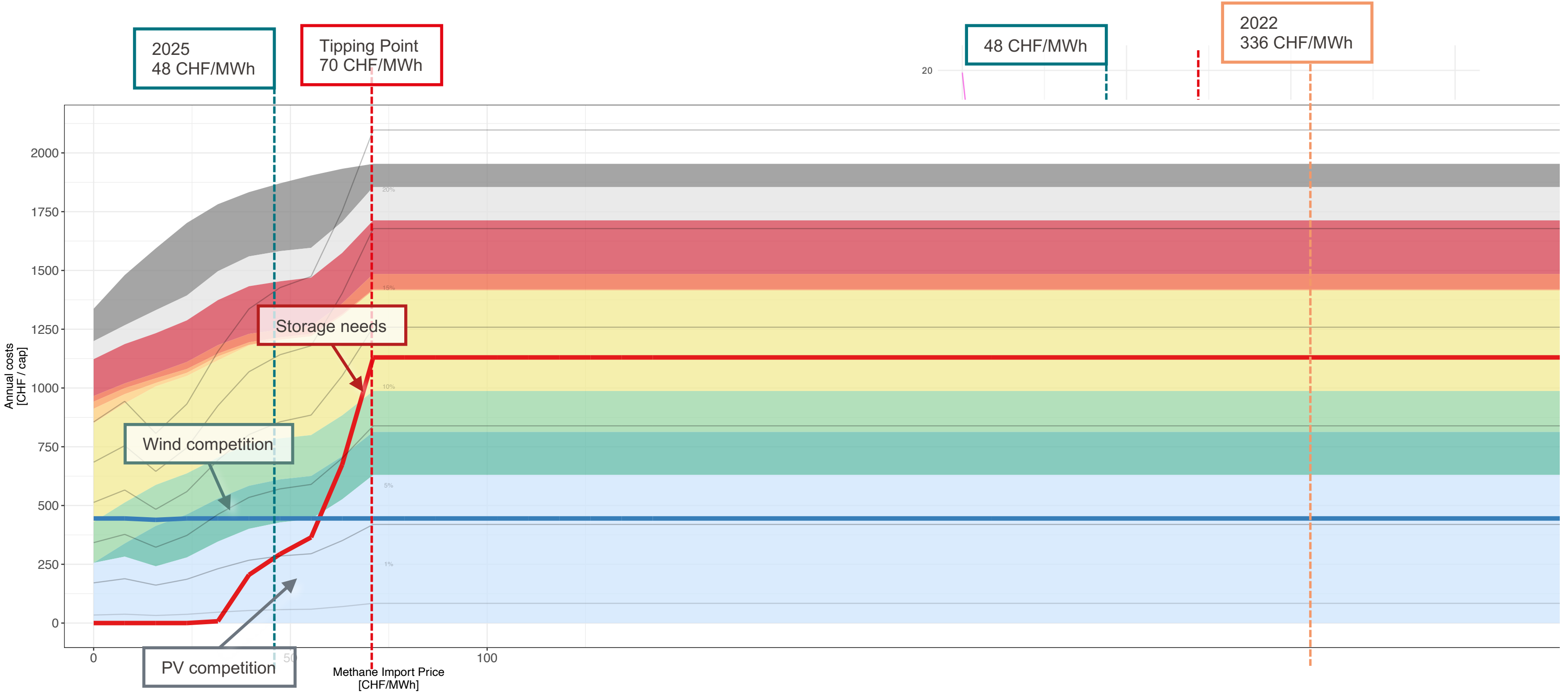
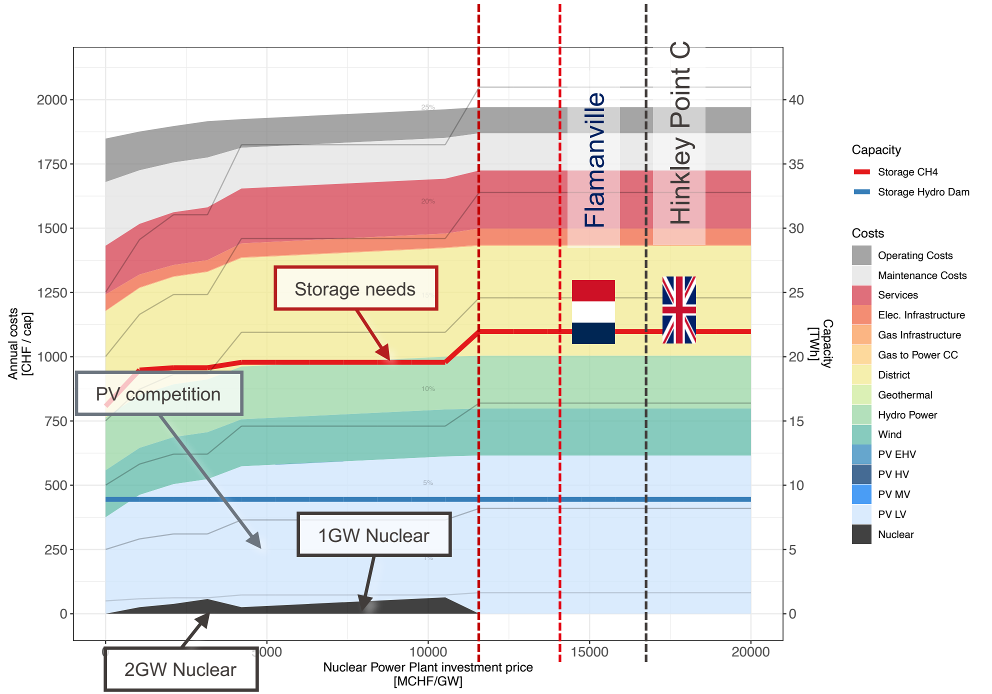
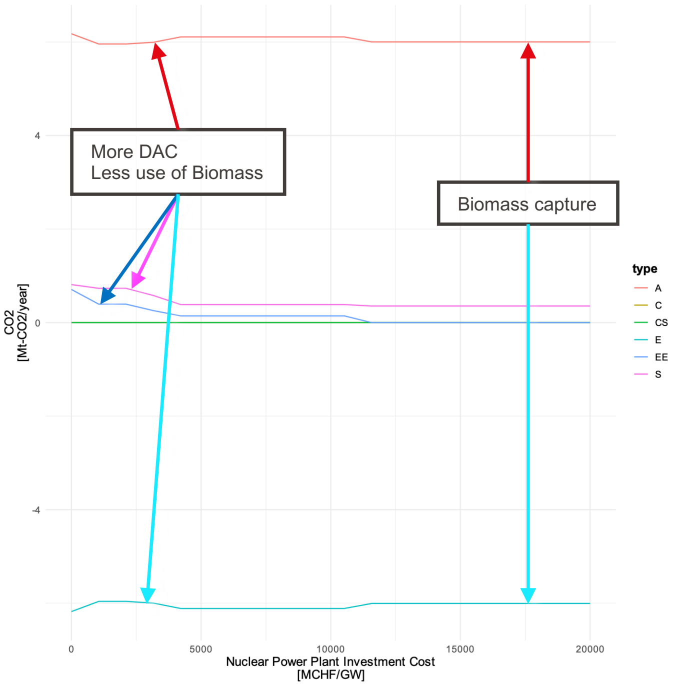
Independence of Switzerland
Critical price of methane import price



Independence of Switzerland
Critical price of nuclear power plants






Une énergie suisse et décarbonnée d'ici à 2050 ?
L'HES-SO et l'EPFL amènent leur éclairage...
Swiss and decarbonized Swiss Energy by 2050? The HES-So and EPFL enlighten the question
According to my research
Selon mes recherches ... c'est impossible !
It is impossible!
tap' tap'
According to ours it is possible!
Selon les notres, c'est possible ! ...
less expensive
et moins cher
and sustainable
et durable
consommation
statistiques
hydro
Ressources
CADASTRE
OMM
éolien
EPFL
EPFL HES-So
HES-So
Pigr.