Environmental and techno-economic assessment of the technology

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Outline

- Techno-economic assessment
- Environmental analysis

Why is a holistic perspective important?

Technical performance (thermal & mechanical)

How does the system perform technically?

Economic feasibility

Is it financially beneficial?

Environmental impact

Is it truly sustainable in the long-term?

- Real-world designs must balance all three for long-term success
  - Optimizing one aspect may compromise another
- Supporting better design decisions, policy development, and sustainable investment

Techno-economic analysis (TEA)

CAPEX

OPEX

ROI

NPV

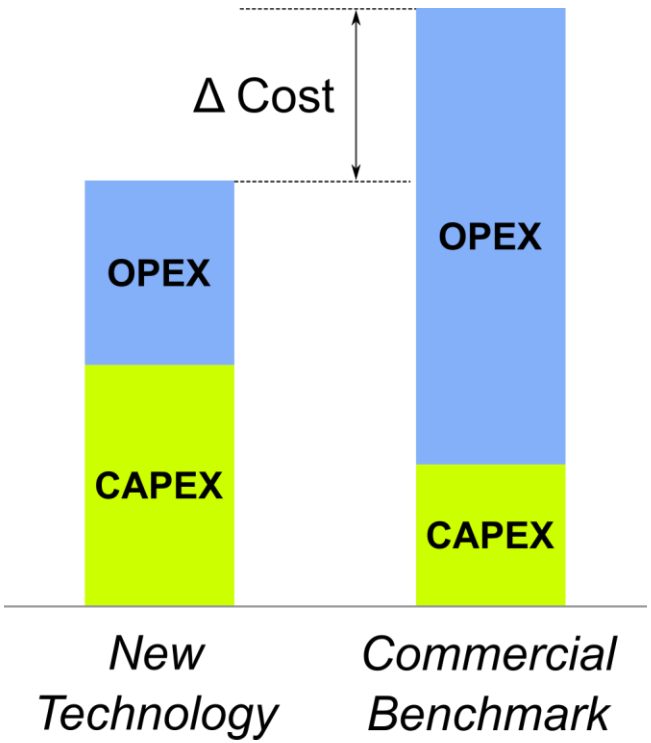
...

Techno-economic analysis (TEA)

= method for evaluating the economic performance of a technology

- **Cost benchmarking**: to demonstrate the cost competitiveness of a new technology
  - Costs of new technology are compared head-to-head against those of existing technology that would compete.
  - Compare to performance-equivalent functional unit → power or energy produced

- Successful commercialization: new technology must be cost-competitive



What would be the new technology (energy geostructures) when compared to the conventional existing technology ?

Techno-economic analysis (TEA)

Cost benchmarking input required:

- **CAPEX**: One-time costs related to the acquisition, construction, or enhancement of fixed assets
- **OPEX**: Ongoing costs for running a project or asset, including maintenance, utilities, salaries, and consumables
- **Bill of quantities**: What specific quantities, materials, and unit costs are needed?

Evaluating the results

- **Net present value (NPV):** it compares the initial investment to the future cash flows it generates, adjusted to their present value using a discount rate to account for time and risk
- **Return of investment (ROI):** refers to the payback period, which is the amount of time it takes for an investment to recover its initial cost through net savings or profits.

Costs

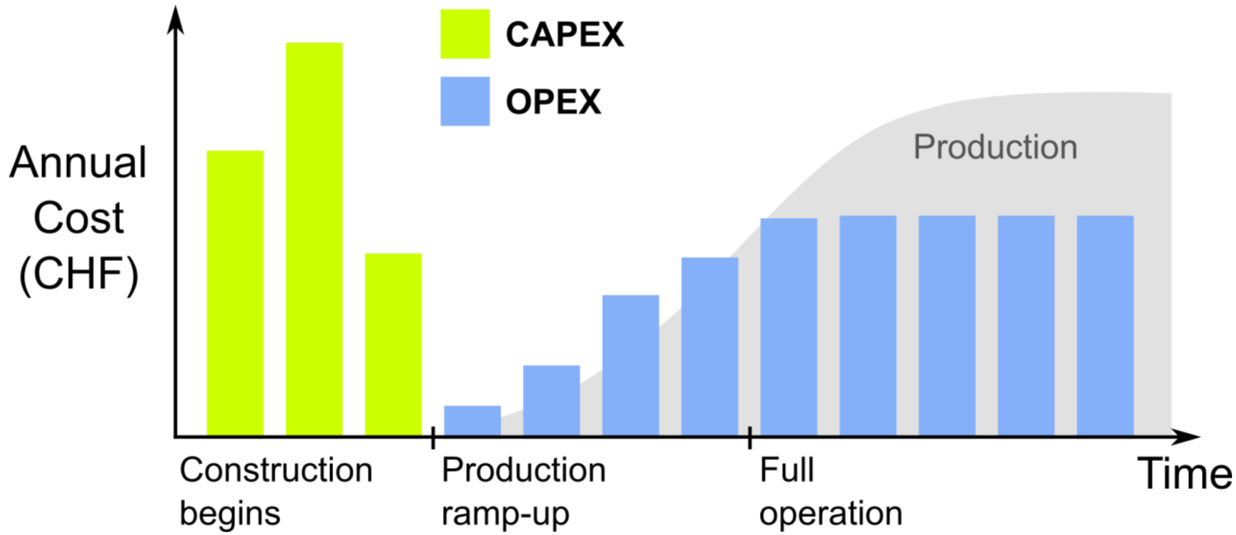
Capital Expenses (CAPEX)

- One-time costs
- Examples: equipment, construction, …

Operating Expenses (OPEX)

- Recurring expenses (fixed or variable)
- Examples: energy, maintenance, …

CAPEX and OPEX expenses happen at different points in a project timeline

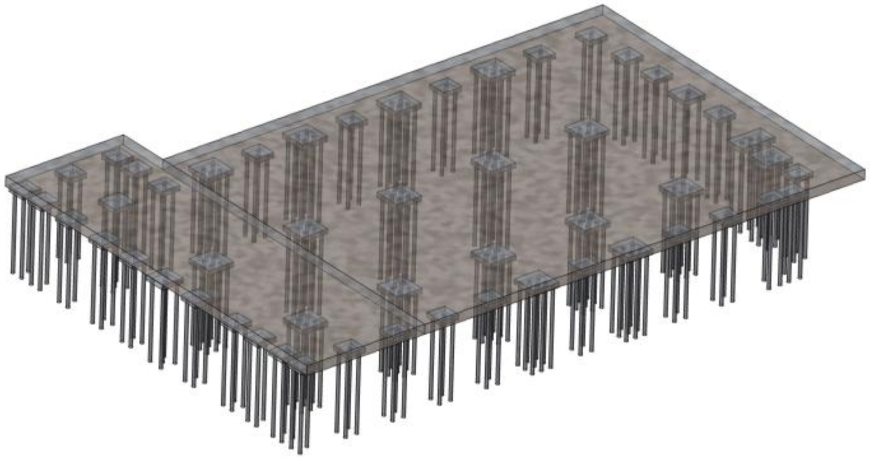


Components of the system: energy piles

Components of an energy piles system:

- Exchanger pipes and fluid
- Header pipes
- Isolant
- Collector
- Stop and regulation valves
- Heat pump and circulation pump

Source image GEOEG



Bill of quantities: example



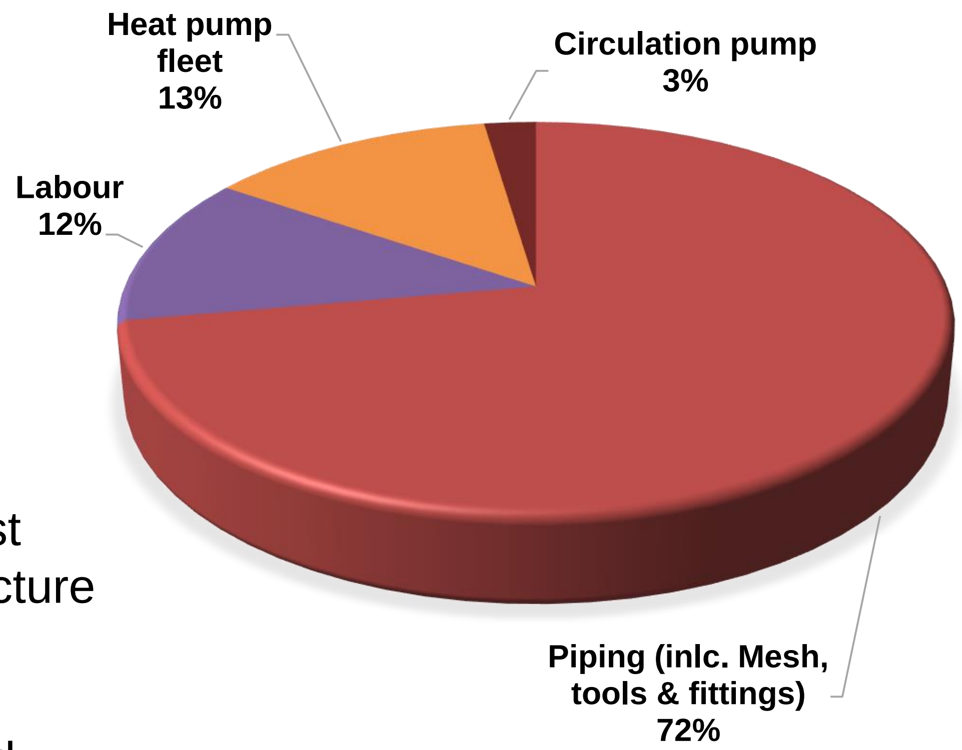

Heat pump	**Power**	**N°**
	300 kW	2

Exchanger pipes	**Diameter**	**Length**
PE-Xa	25 x 2.3 mm (SDR 11)	58 km



CAPEX: example

Overview components	Cost [CHF]
Piping (incl. mesh, tools & fittings)	826’180
Labour	140’975
Heat pump fleet	150’000
Circulation pump	26’826
TOTAL	**1’143’981**

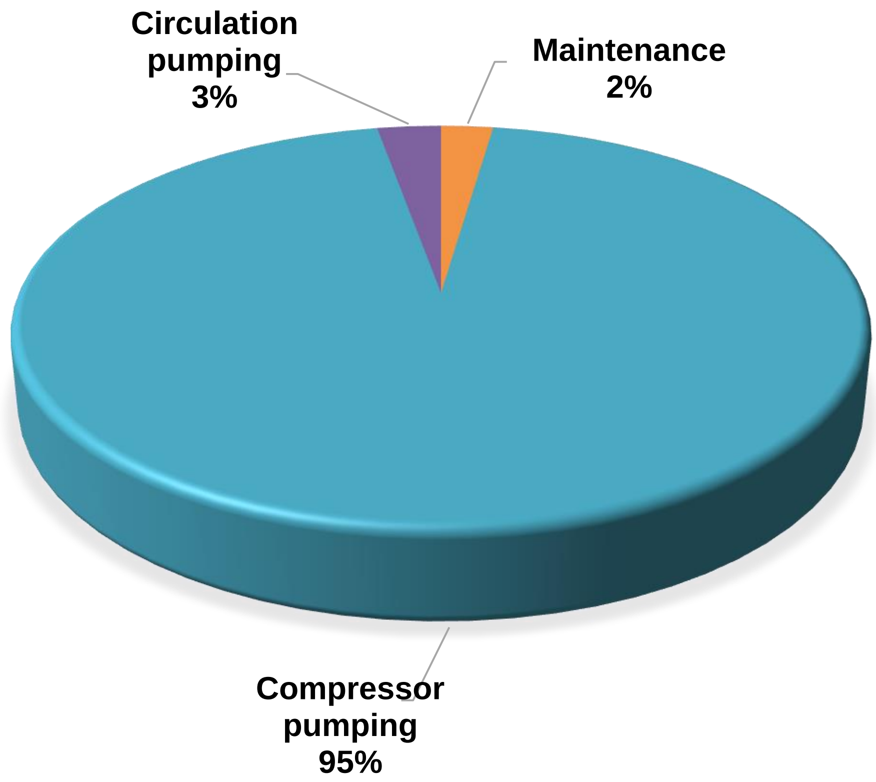


- ***Piping***: depend on pipe diameter and length required
- ***Manual labour***: local hourly labour cost and time required to equip the geostructure
- ***Heat pump fleet***: depend on required power
- ***Circulation pump***: depend on required pumping power (calculate from head losses)

OPEX: example

Overview components	Cost [CHF/year]
Maintenance	6’240
Compressor pumping	255’354
Circulation pumping	7’627
TOTAL	**269’221**

- ***Circulation pumping***: electricity to run the circulation pump
- ***Compressor pumping***: electricity to run the heat pump
- ***Maintenance***: maintenance of heat pump



Cash flow in energy geostructures

Cash flow can come from two main sources:

- **Operational cost savings:** When energy geostructures replace conventional systems, they reduce annual operating costs.

Yearly cash flow = $OPEX_{Ex,\ tech} - OPEX_{EG}$

- **Selling extracted energy:** if all the thermal energy is sold (e.g., in energy tunnels), revenue is generated directly.

$$Q_{supplied} = \dot{Q}_{supplied} \cdot t_{op,yr}$$

Energy [kWh]

Heat extraction rate [kW]

Yearly operation time [hours]

$$Revenue = Q_{supplied} \cdot Heat\ selling\ price$$

Yearly cash flow = Revenue from heat sales – $OPEX_{EG}$

NPV and ROI: calculation

Net present value (NPV)

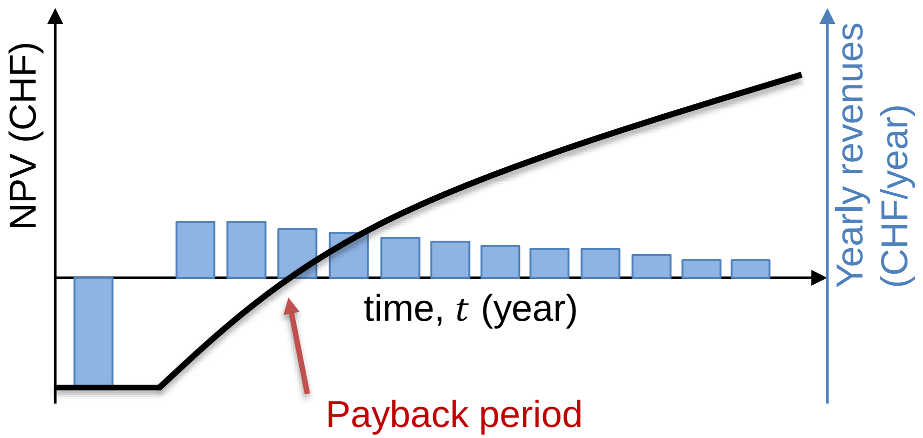
- Assesses profitability of the system
- Defined as:

$$NPV = -I_0 + \sum_{t=0}^{T_{service}} \frac{C_t}{(1+i)^t}$$

  - t = time (years)
  - I_0 = initial investment of geothermal activation
  - $T_{service}$ = service lifetime
  - C_t = yearly cash flow
  - i = sum of inflation and interest rate

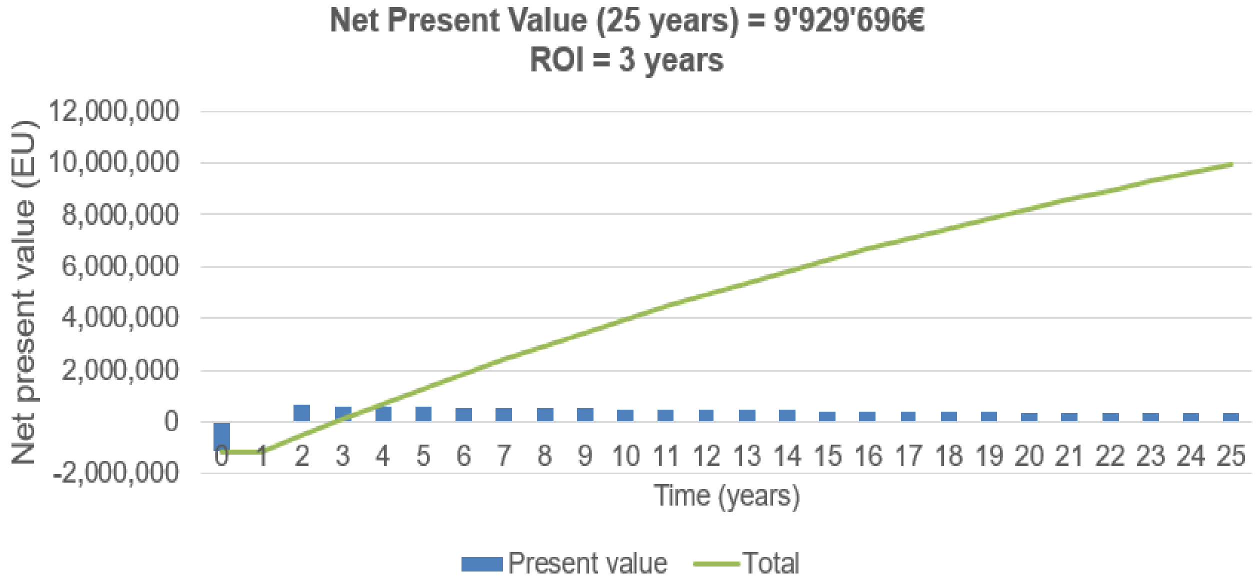
Return on investment (ROI)

- Assess the investment yield
- %: percentage return relative to the initial investment at a certain moment in time
- **Payback period**: time it takes to recoup the initial investment from net savings



NPV and ROI: example

Energy Piles (up to heat pump)	Cost [CHF]
CAPEX	-1’143’981
OPEX per year	-269’221
Cash flow per year	942’709
TOTAL investment	**-1’143’981**
TOTAL per year	**673’488**

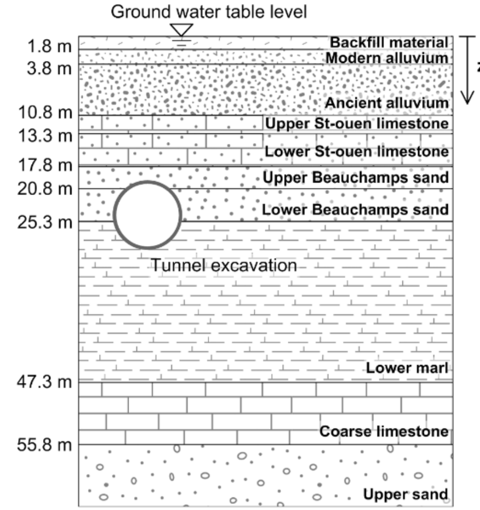


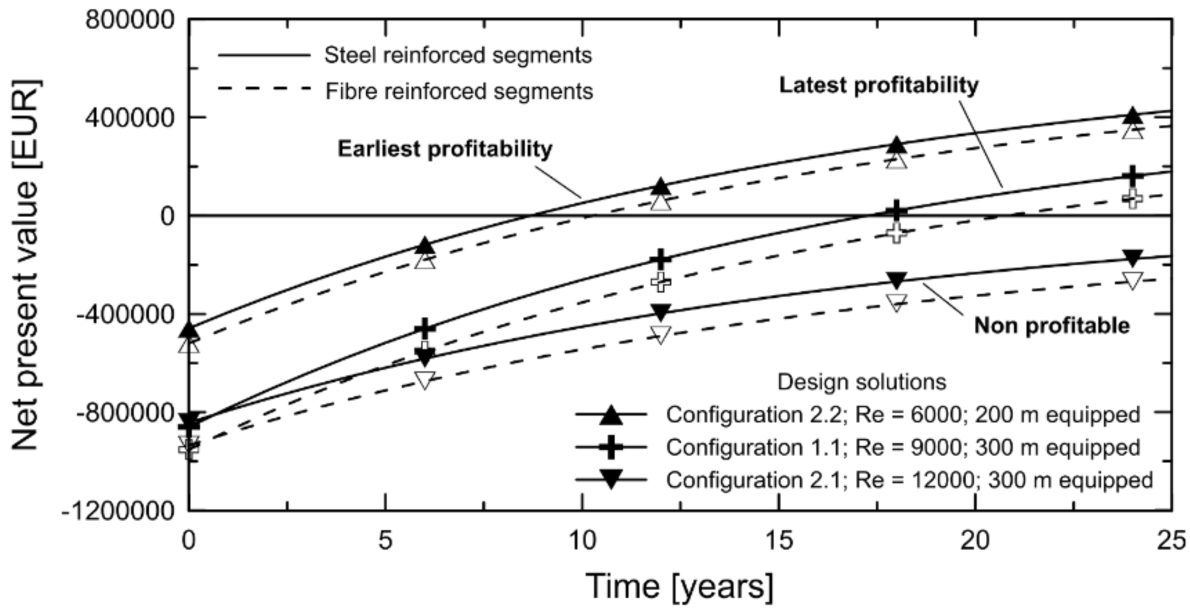
Example: Grand Paris Express

Cousin et al. 2019

- Energy tunnel application
  - Tunnel energy segmental linings

- Demonstrate **economic attractiveness** of the application & justify benefit of installing energy geostructures instead of conventional geostructure.
  - Analysis of costs and profitability considering different design solutions

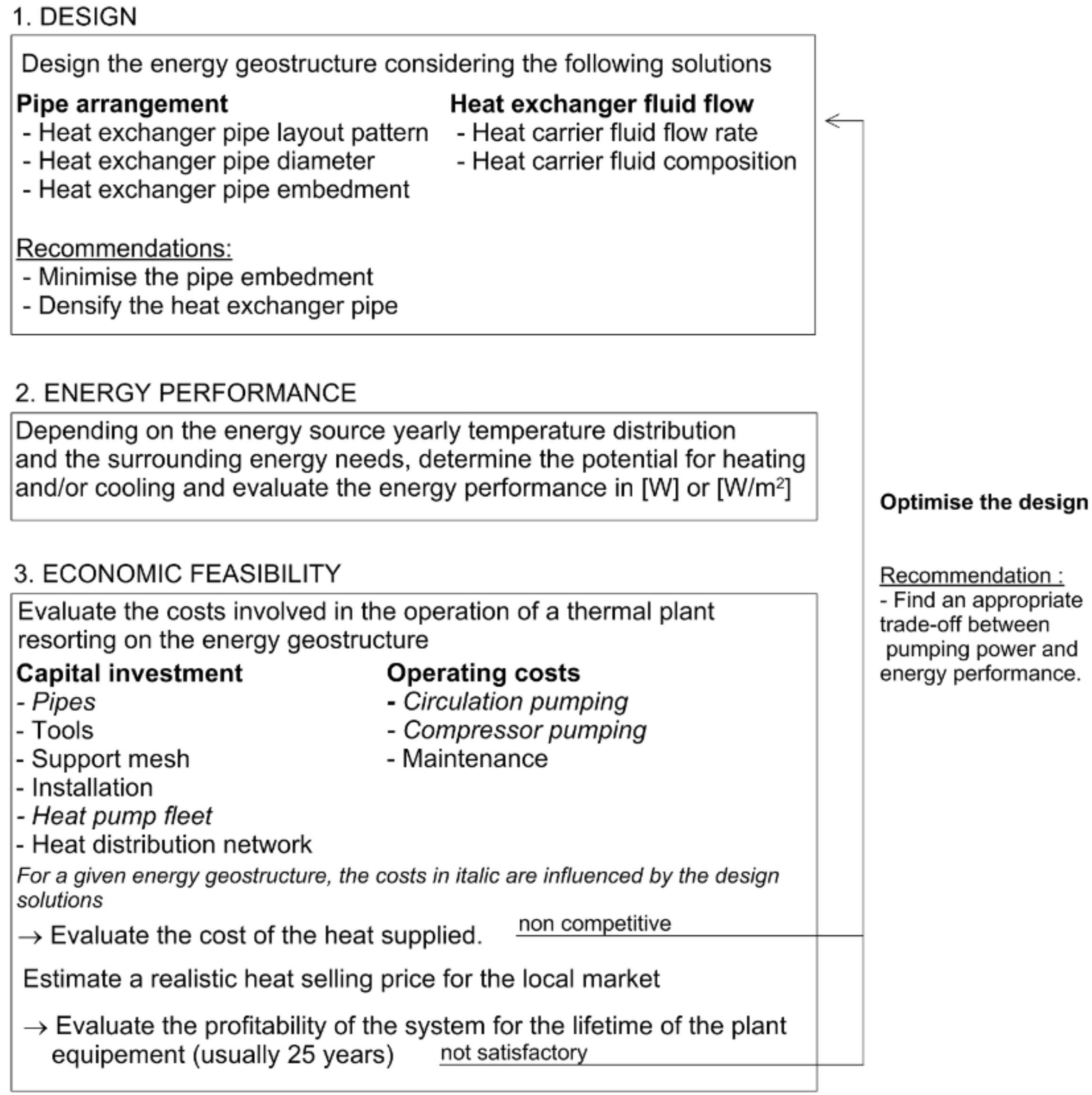




Example: Grand Paris Express

Cousin et al. 2019

Economic oriented design process for energy geostructures



Environmental analysis

Environmental analysis

- **LCA** = Life Cycle Analysis
  - Considering all environmental impact in different life phases:
    - Production, Distribution, Use, Disposal
  - Considers impact on:
    - Climate change, Human health, Resources, Ecosystem quality
    - Impact on climate change evaluated in terms of kgCO_2-eq

- Embodied carbon
  - Production
  - Distribution
  - Disposal
- Operational CO_2

Embodied carbon: Production example

Material or process description	**Value [t]**	**Emission factor [kgCO2e/t]**	**Total GHGs emissions [kgCO2eq]**
Exchanger pipes	57.4	202	11’587
Isolant	3.86	2’460	9’491
Collector	1.18	202	238
Valves	1.10	938	1’035
Heat pump-Copper	1.1	1’445	1’602
Heat pump-PVC	0.05	1’870	90
Heat pump-Steel	4.56	2’211	10’082
Heat pump-Refrigerant	0.15	1’300	202
Circulation pump-Cast iron	0.46	1’800	828

Embodied carbon: Distribution example

Components	From where to where?	Weight [t]	Distance [km]	Vehicle size	Emission factor [kgCO2e/ tkm]	Total GHGs emissions [kgCO2eq]
Exchanger pipes	From assembly to customer	57.4	100	Road - Heavy Goods Vehicle (>20 t Gross Vehicle Weight)	0.092	528
Isolant	From assembly to customer	3.86	100	Road - Urban truck (3.5-7.5 t Gross Vehicle Weight)	0.37	143
Collector	From assembly to customer	1.18	100	Road - Urban truck (3.5-7.5 t Gross Vehicle Weight)	0.37	44
Valves	From assembly to customer	1.10	100	Road - Urban truck (3.5-7.5 t Gross Vehicle Weight)	0.37	41
Heat pump	From assembly to customer	2.85	1’000	Air - Medium haul (1’000-3’700km)	0.7	1’995
Circulation pump	From assembly to customer	0.46	100	Road - Urban truck (3.5-7.5 t Gross Vehicle Weight)	0.37	17

Operational CO_2: Use example

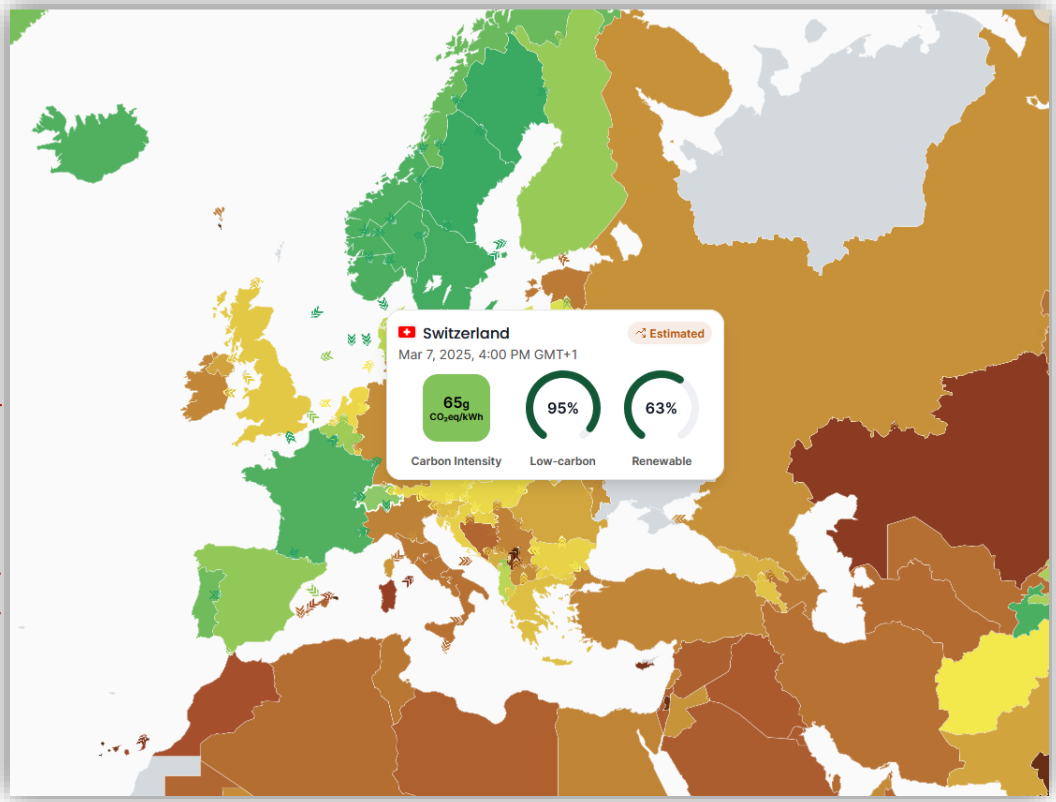
Material or process description	Value [kWh]	Emission factor [kgCO2e/kWh]	Total GHGs emissions [kgCO2eq]
Operational energy use to heat/cool the building	1’334’538	0.365	487’106

varies per location and time

Emission factor of electricity

Depending on country of energy geostructure
→ Where is the electricity coming from?

- Useful tool: [electricity maps]



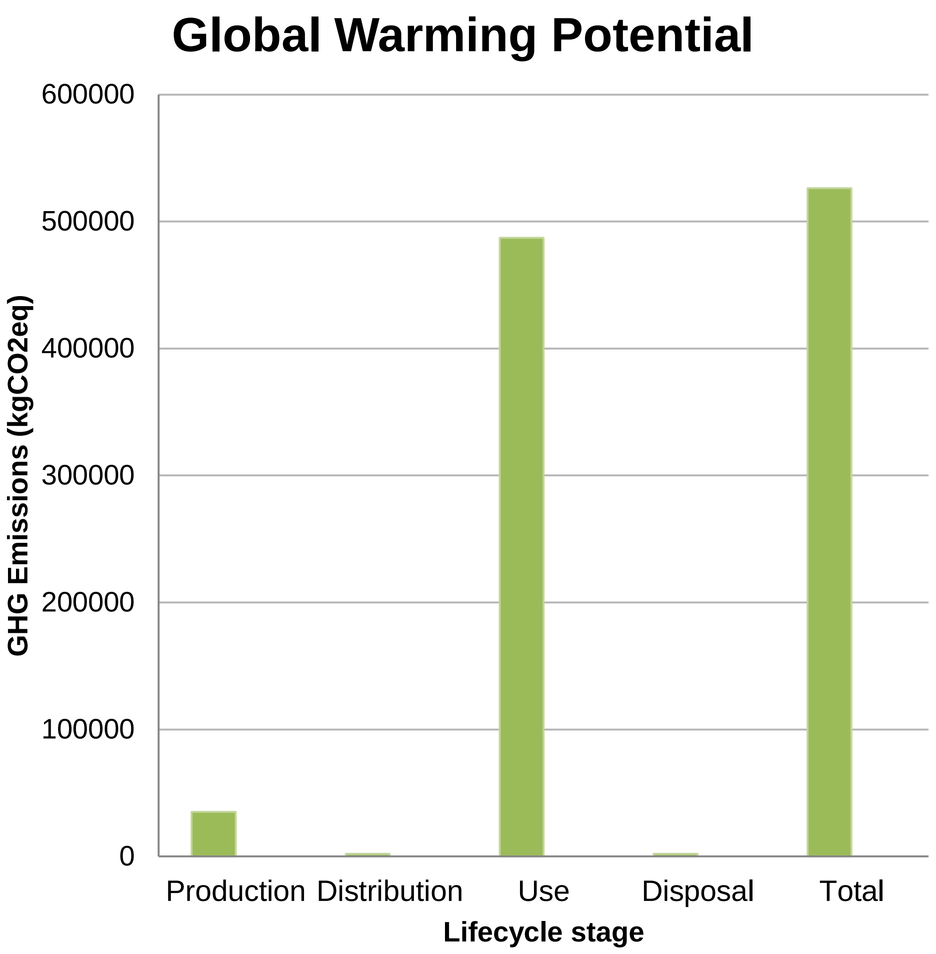
Screenshot 07/03/2025 as example

Embodied carbon: Disposal example

Material or process description	Disposal process description	Value [t]	Emission factor [kgCO2e/t]	Total GHGs emissions [kgCO2eq]
Exchanger pipes	residual material landfill	57.4	33	1’893
Isolant	residual material landfill	3.86	33	127
Collector	residual material landfill	1.18	33	39
Valves	recycling	1.10	0	0
Heat pump-Copper	recycling	1.1	0	0
Heat pump-PVC	residual material landfill	0.05	33	2
Heat pump-Steel	recycling	4.56	0	0
Heat pump-Refrigerant	residual material landfill	0.15	128	20
Circulation pump-Cast iron	recycling	0.46	0	0

Global warming potential: example

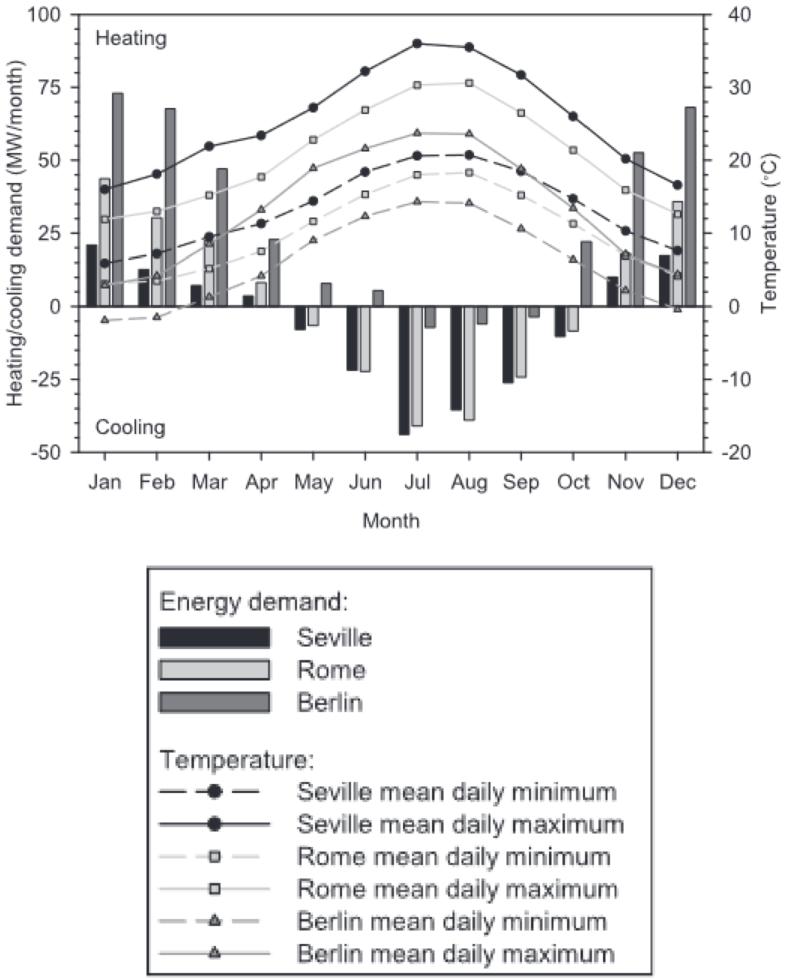
Summary	Total GHGs emissions [kgCO2eq]
Production	35’155
Distribution	2’012
Use	487’106
Disposal	2’081
TOTAL	**526’354**



Example: LCA for 3 climates

Sutman et al. 2020

- Energy piles in 3 diverse climatic conditions: Spain – Rome – Berlin
- Performed LCA for the energy pile foundation in the 3 situations
  - Full LCA: material extraction, transportation, execution, use and disposal
  - Used Software SimaPro 8.0.3
  - Following international standards ISO 14040, 2006 and ISO14044
- Design lifetimes
  - Building – 50 years
  - Electric heating/cooling system – 20 years



Example: LCA for 3 climates

Sutman et al. 2020

Conventional systems

LCI of the conventional systems for the three reference cities (SV: Seville; RM: Rome; BE: Berlin).

Life Cycle Step	Input	Amount SV/RM/BE	Unit	Flow from ecoinvent Database
Material Production	Concrete	6,51	m^3	Concrete, normal {CH}
	Rebars	40,00	t	Reinforcing steel {GLO}
	Boiler	0,05/0,10/0.20	–	Oil boiler, 10 kW {CH}
Transportation	Concrete	795,00	tkm	Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}
	Rebars	2,00	tkm	
	Machines	95,30	tkm	
	Transport of PipesTransport (EOL)	0,19	tkm	
		797,19	tkm	
Execution	Excavation	34,00	m^3	Excavation, hydraulic digger {GLO}
	Drilling	1,00	hr	Machine operation, diesel, >=74.57 kW, high load factor {GLO}
Use	Heating	71,19/163,26/364,98	MWh	Heat, central or small-scale, natural gas {Europe without Switzerland}
	Cooling	142,44/138,93/20,88	MWh	Electricity, medium voltage {ES/IT/DE}
End of Life (EOL)	Boiler	12,20	kg	Used industrial electronic device {CH}
		0,15	kg	Inert waste, for final disposal {CH}
		3,35	kg	Waste reinforcement steel {CH} | collection for final disposal
		2,65	kg	Waste reinforcement steel {CH}| treatment of, recycling
		0,05	kg	Waste plastic, mixture {Europe without Switzerland}
		0,40	kg	Inert waste, for final disposal {CH}
	Reinforced concrete	15,93	t	Waste reinforced concrete {Europe without Switzerland}
		13,70	t	Waste concrete {Europe without Switzerland}
		−2,23	t	Recycling concrete (Rock crushing {RER}| processing
		5,60	t	Waste reinforcement steel {RoW}
	Soil	4,61	kg	Drilling waste {CH}| treatment of, residual material landfill

Example: LCA for 3 climates

Sutman et al. 2020

Energy piles systems

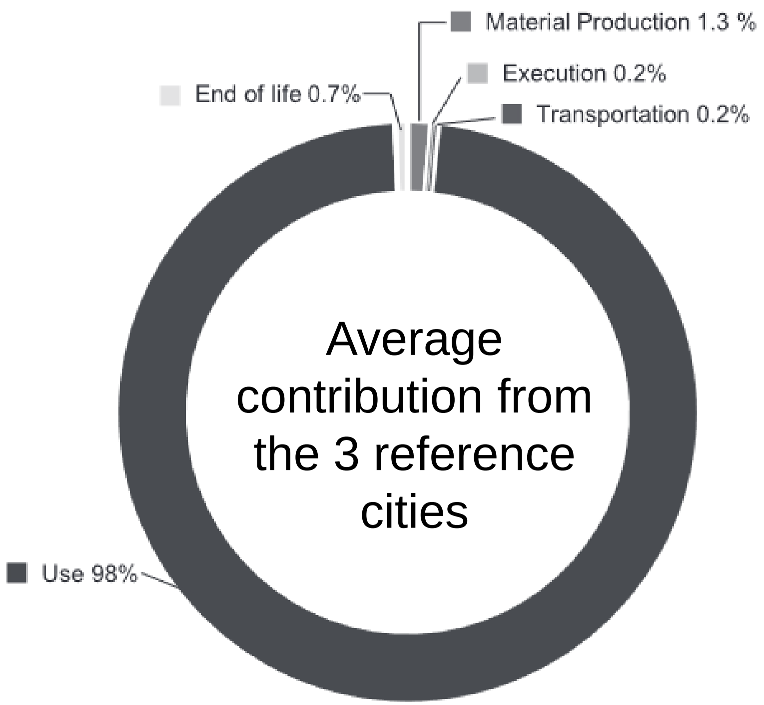
LCI of energy piles for the three reference cities (SV: Seville; RM: Rome; BE: Berlin).

Life Cycle Step	Input	Amount SV/RM/BE	Unit	Flow from ecoinvent Database
Material Production	Concrete	6,50	m^3	Concrete, normal {CH}
	Rebars	40,00	kg	Reinforcing steel {GLO}
	GSHP	0,01/0,02/0.04	–	Heat pump, 30 kW {RER}
	Auxiliary System	0,00/0,26/0.66	-kg	Auxiliary heating unit, electric, 5 kW {CH}
	Refrigerant	3,94	kg	Refrigerant R134a {RER}
	Pipes	3,80	m	Extrusion, plastic pipes {RER}
		38,40		Polyethylene pipe, DN 200, SDR 41 {GLO}
Transportation	Concrete	795,00	tkm	Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}
	Rebars	2,00	tkm	
	Machines	95,30	tkm	
	Transport of Pipes	0,19	tkm	
	Transport (EOL)	797,19	tkm	
Execution	Excavation	34,00	m^3	Excavation, hydraulic digger {GLO}
	Drilling	1,00	hr	Machine operation, diesel, >=74.57 kW, high load factor {GLO}
Use	Heating			
	Renewable	53,14/109,14/108,81	MWh	Energy, geothermal, converted
	Heat pump	19,26/56,08/104,39	MWh	Electricity, medium voltage {ES, IT, DE}
	Auxiliary	0,00/0,00/80,39	MWh	Electricity, medium voltage {ES, IT, DE}
	Cooling			
	Renewable	30,93/108,81/17,91	MWh	Energy, geothermal, converted
	Heat pump	5,31/24,97/3,79	MWh	Electricity, medium voltage {ES, IT, DE}
	Auxiliary	6,48/6,45/0,00	MWh	Electricity, medium voltage {ES, IT, DE}
End of Life (EOL)	GSHP	20,40	kg	Used industrial electronic device {CH}
		3,29	kg	Inert waste, for final disposal {CH}
		7,94	kg	Waste reinforcement steel {CH}| collection for final disposal
		6,26	kg	Waste reinforcement steel {CH}| treatment of, recycling
		0,29	kg	Waste plastic, mixture {Europe without Switzerland}
		0,15	kg	Inert waste, for final disposal {CH}
		1,00	kg	Used refrigerant R134a {GLO}|
	Reinforced concrete	15,90	t	Waste reinforced concrete {Europe without Switzerland}
		13,70	t	Waste concrete {Europe without Switzerland}
		−2,23	t	Recycling concrete (Rock crushing {RER}| processing
		5,60	kg	Waste reinforcement steel {RoW}
	Pipes	32,70	kg	polyethylene/polypropylene product {CH}
		0,53	kg	PE (waste treatment) {GLO}| recycling of PE
	Soil	4,61	t	Drilling waste {CH}| treatment of, residual material landfill

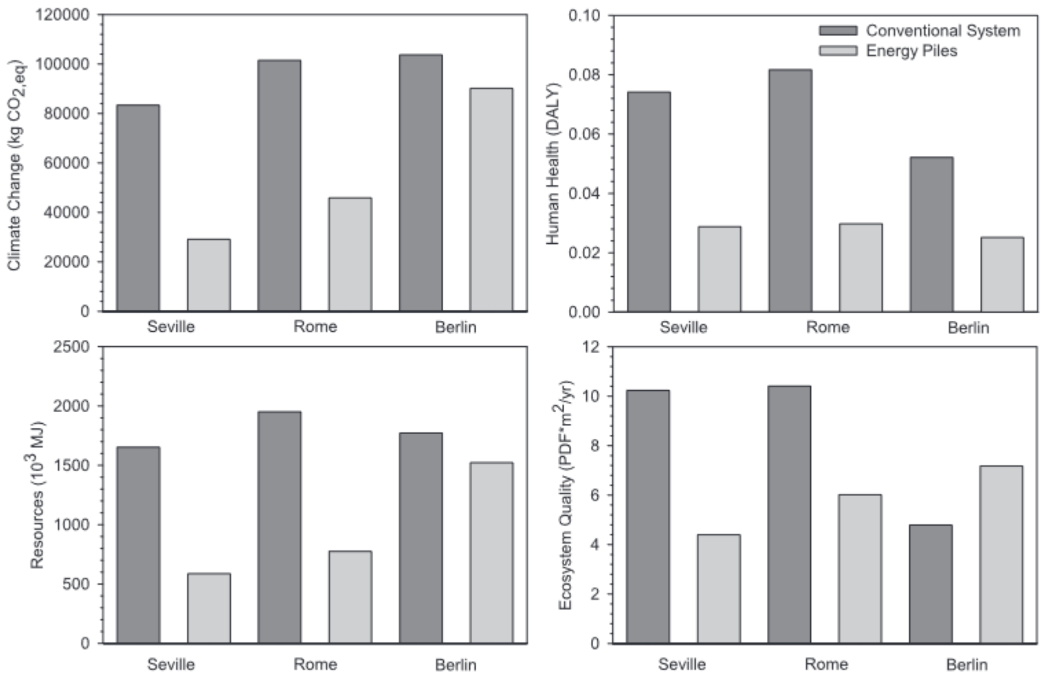
Example: LCA for 3 climates

Sutman et al. 2020

- Dominant contribution from 'use' phase to total environmental impact in terms of climate change from different life cycle stages



- Results of LCA in terms of four endpoint indicators. Environmental performance of systems strongly depends on country and heating and cooling demands.



Summary

Summary

- Next to technical evaluation, **economical and environmental assessment** is of critical importance for stakeholders and design decisions

- **Cost benchmarking** versus a traditional alternative is often used as a method to demonstrate the interest of the novel technology

- The **return of investment** is estimated between 3 to 10 years for energy geostructures, but should be assessed on a case-by-case basis

- The **'Use' phase** of the life cycle analysis for energy geostructures is often dominant in the environmental assessment but it depends on local conditions and varies over time

- Significant savings in terms of kgCO_2eq can be achieved by obtaining heat from energy geostructures (15 gCO_2eq/kWh) compared to heating systems that rely on gas or electricity (200 gCO_2eq/kWh) (Edenhofer et al. 2011).