Design of Geothermal Energy Conversion Systems with a Life Cycle Assessment Perspective

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GEOTHERM

Context

- Future development of EGS as an alternative energy source
- Cogeneration
  - Electricity (21% of energy cons.)
  - Space heating and domestic hot water (40% of energy cons.)
- Conceptual energy conversion system design
  - Economic competitiveness
  - Conversion efficiency
  - Environmental impacts

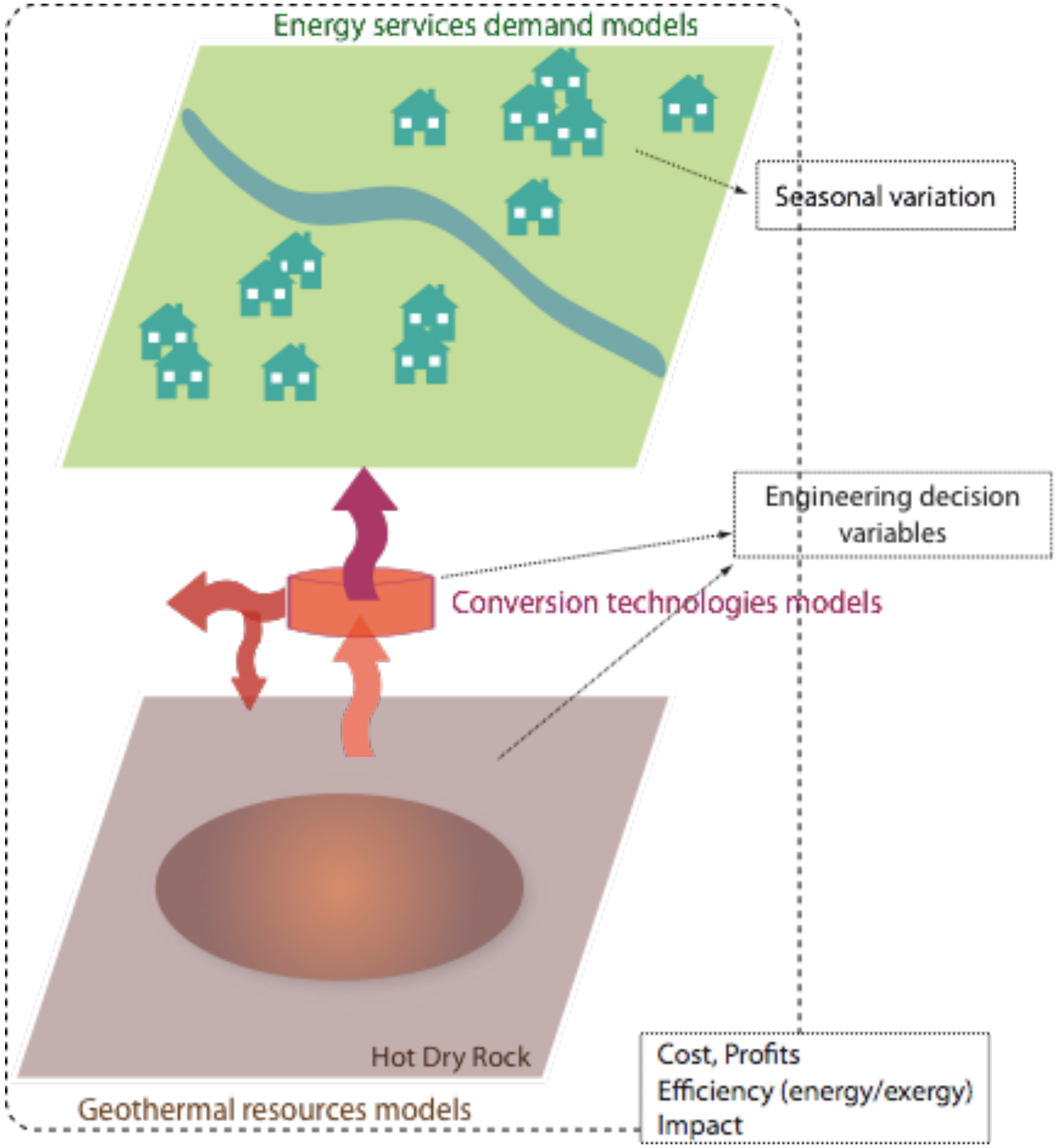
➡ *Systematic methodology for system design accounting for site-specific conditions*

Objectives

- Methodology integrates$^{(1)}$:
  - Services to be supplied
  - Geothermal resources with geological characteristics
  - Energy conversion technologies

➡ *Identify environomic optimal configurations for mature EGS technology*

- *Conversion technologies to be used*
- *Exploitation depth, district heating size*
- *Average conditions for Switzerland*



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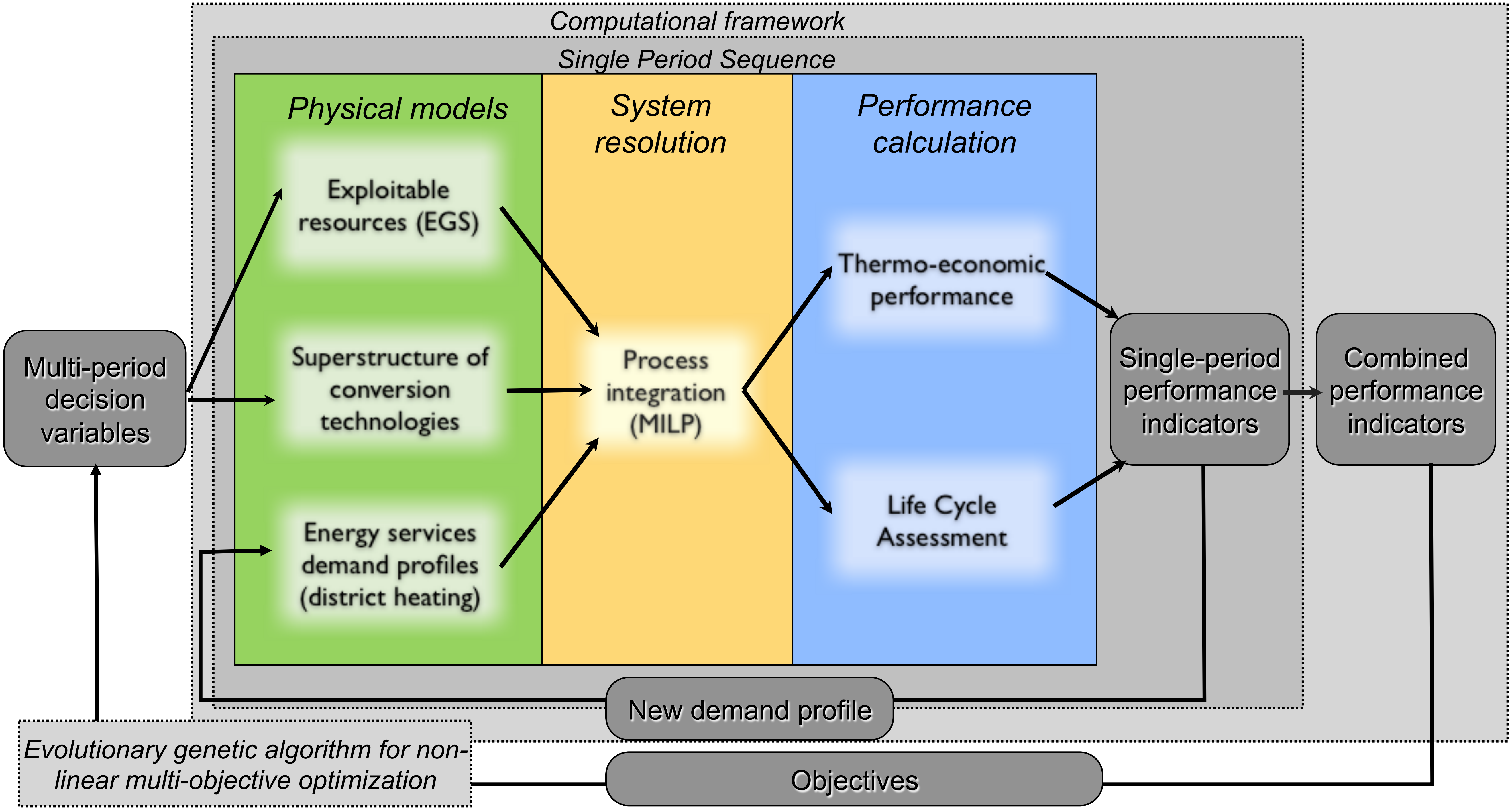
(1): Gerber, L. and Maréchal, F. «Defining optimal configurations of geothermal systems using process design and process integration techniques», *Applied Thermal Engineering*, doi: 10.1016/j.applthermaleng.2011.11.033, 2011

Process design environment



Computational framework

Single Period Sequence

Physical models

Exploitable resources (EGS)

Superstructure of conversion technologies

Energy services demand profiles (district heating)

System resolution

Process integration (MILP)

Performance calculation

Thermo-economic performance

Life Cycle Assessment

Multi-period decision variables

Single-period performance indicators

Combined performance indicators

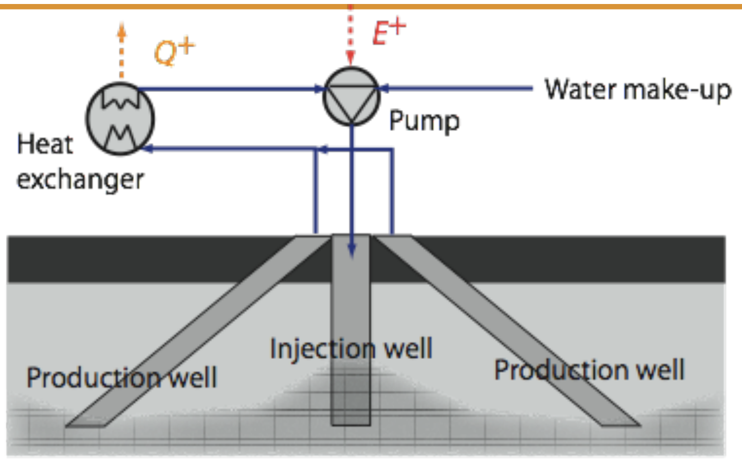
New demand profile

Evolutionary genetic algorithm for non-linear multi-objective optimization

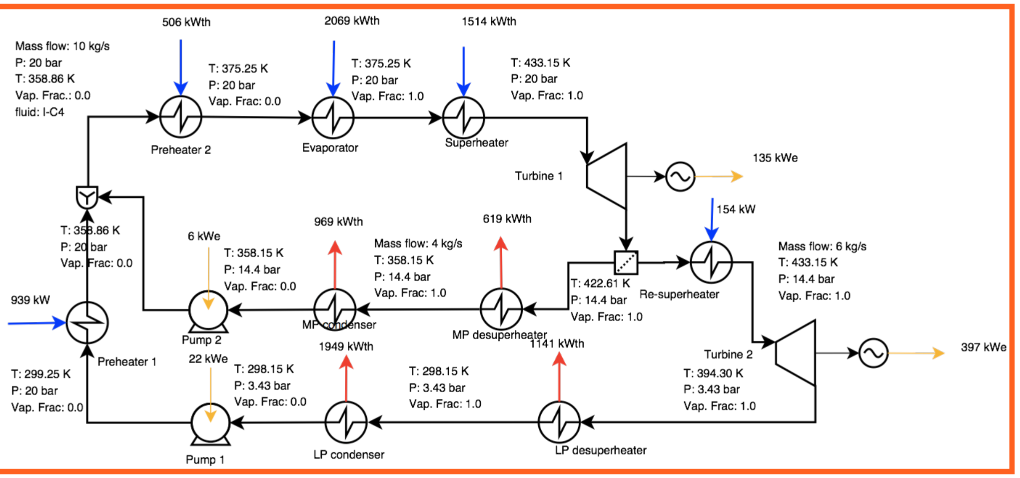
Objectives

Physical models

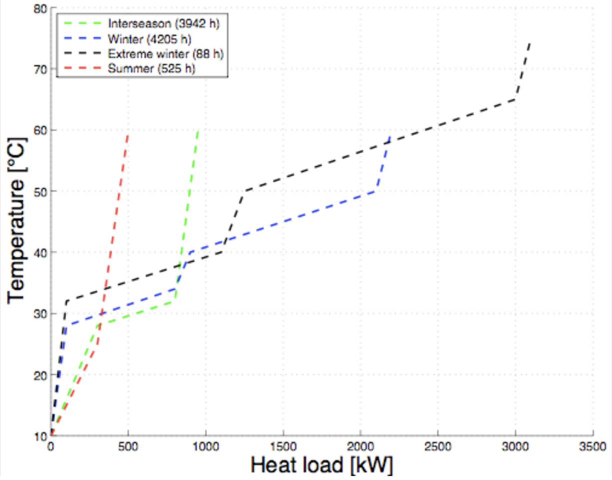
- Resources
  - Hot Dry Rock , 3-wells system for EGS exploitation(1)
  - Variable depth (3000-10000m)
  - Expected mass flow rate (90 kg/s), gradient (0.035°C/m)



- Technologies
  - Database of conversion technologies:
    - 1&2-flash, ORC (simple, draw-off, 2-stages, supercritical), Kalina
  - Model by flow-sheeting software



- Demand
  - Seasonal profiles (GIS-based method for urban areas(2))
    - Space heating and hot water (district heating) as a constraint
  - Variable design size (0-60 MW)



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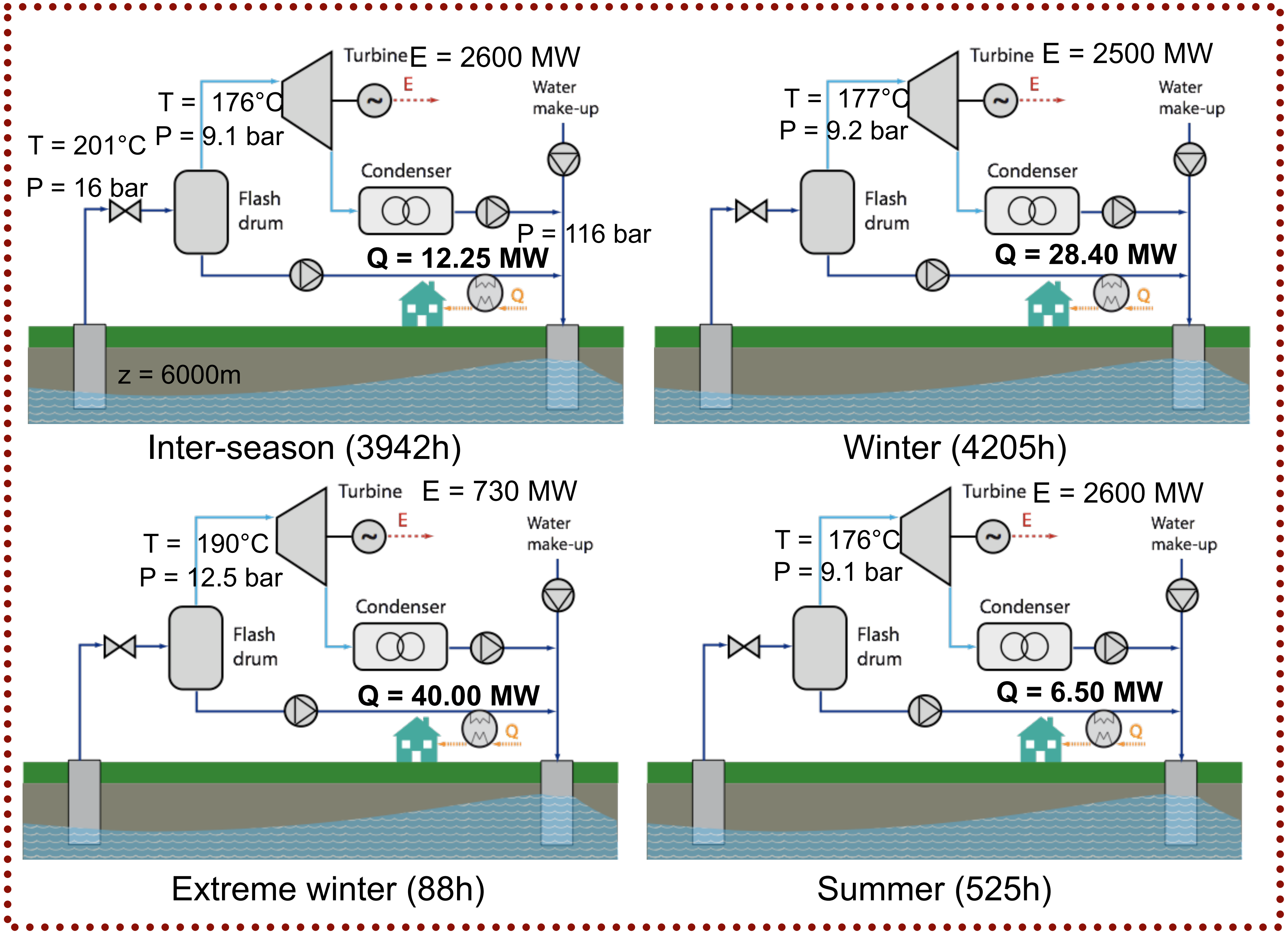
(1): Tester, J. et al. «The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems in the 21st Century», *MIT technical report*, 2006

(2): Girardin, L. et al. «EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas», *Energy*,25, pp. 830-840, 2011

System design and performances

- Integration of 3 components for each period:



Inter-season (3942h)

Winter (4205h)

Extreme winter (88h)

Summer (525h)

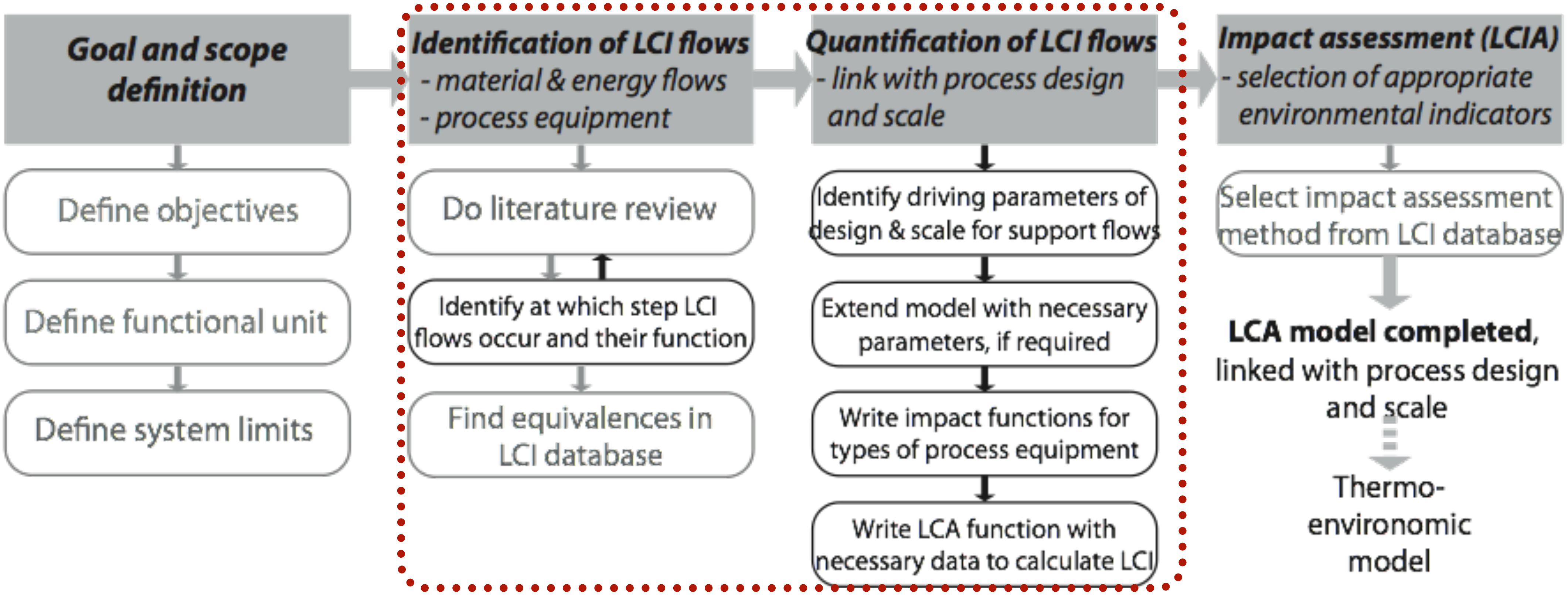
- *Investment cost*
- *Operating cost*
- *Profit*

- *Exergy efficiency*
- *Energy efficiency*
- *Electrical efficiency*

- *Environmental impacts*

Life Cycle Assessment model(1) (1)

- Impact quantification of a product/system/service on its overall life cycle and related to its function



Goal and scope definition

Define objectives

Define functional unit

Define system limits

Identification of LCI flows
- material & energy flows
- process equipment

Do literature review

Identify at which step LCI flows occur and their function

Find equivalences in LCI database

Quantification of LCI flows
- link with process design and scale

Identify driving parameters of design & scale for support flows

Extend model with necessary parameters, if required

Write impact functions for types of process equipment

Write LCA function with necessary data to calculate LCI

Impact assessment (LCIA)
- selection of appropriate environmental indicators

Select impact assessment method from LCI database

LCA model completed, linked with process design and scale

Thermo-environomic model

$$\begin{bmatrix} F_{1,1} & \dots & F_{1,n} \\ \dots & \dots & \dots \\ F_{m,1} & \dots & F_{m,n} \end{bmatrix} * \begin{bmatrix} E_1 \\ \dots \\ E_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \dots \\ I_m \end{bmatrix} \longrightarrow I_{tot} = \sum_{i=1}^{m} I_i * w_i$$

E_i: cumulated emission/extraction i from LCI

$F_{i,j}$: impact factor to transform substance i in impact category j

I_j: impact category j

w_i: weighting factor to add category i to single score impact I_{tot}

Chosen impact assessment methods:

1. IPCC07 - Global Warming Potential, 100 years, in kg-CO2-eq
2. Ecoindicator99-(h,a) - human health, ecosystem quality, non-renewable resources, aggregated in pts

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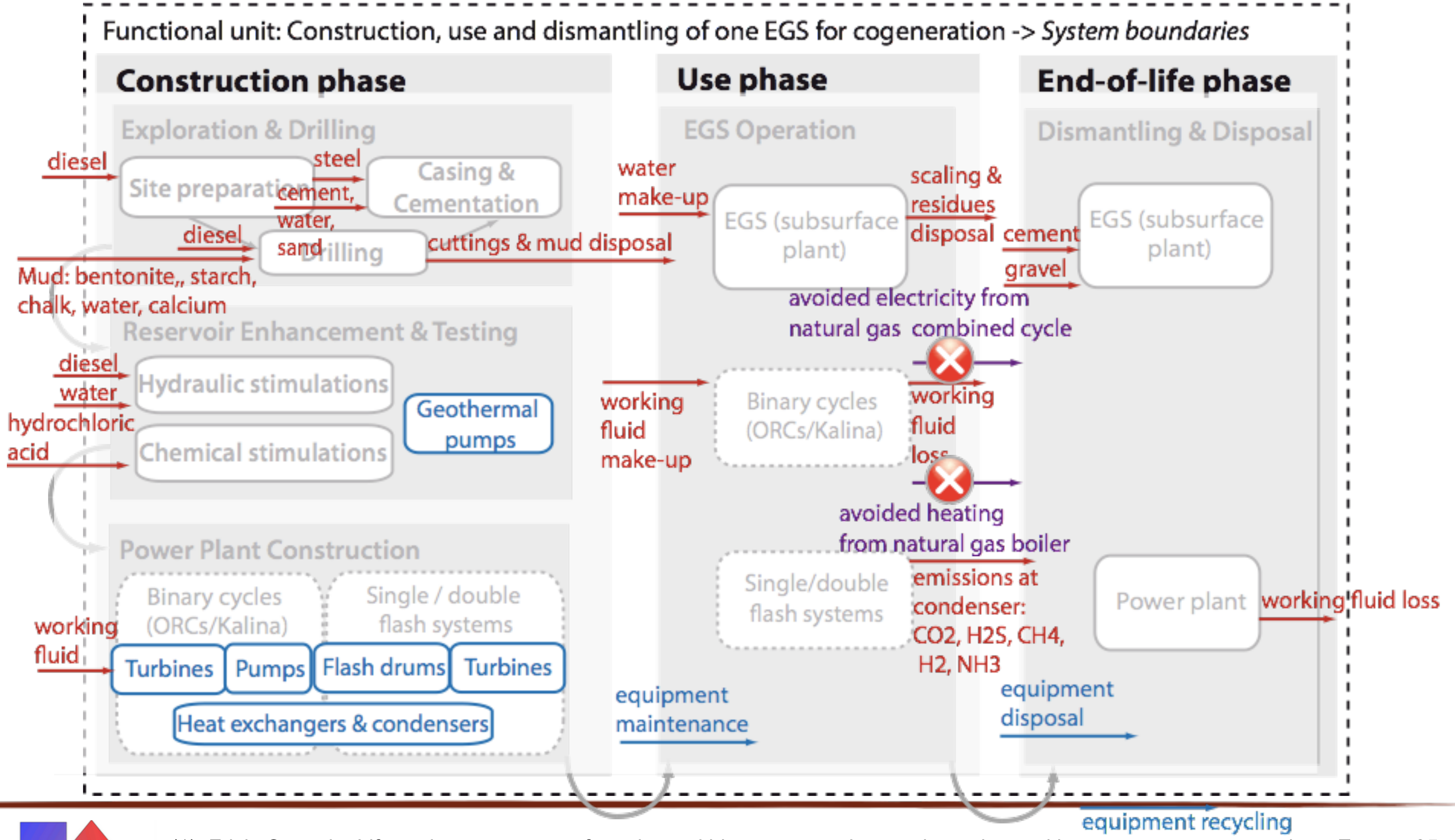
(1): Gerber, L. et al. «Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass», *Computers & Chemical Engineering*, 35, pp. 1265-1280, 2011

Life Cycle Assessment model (2)

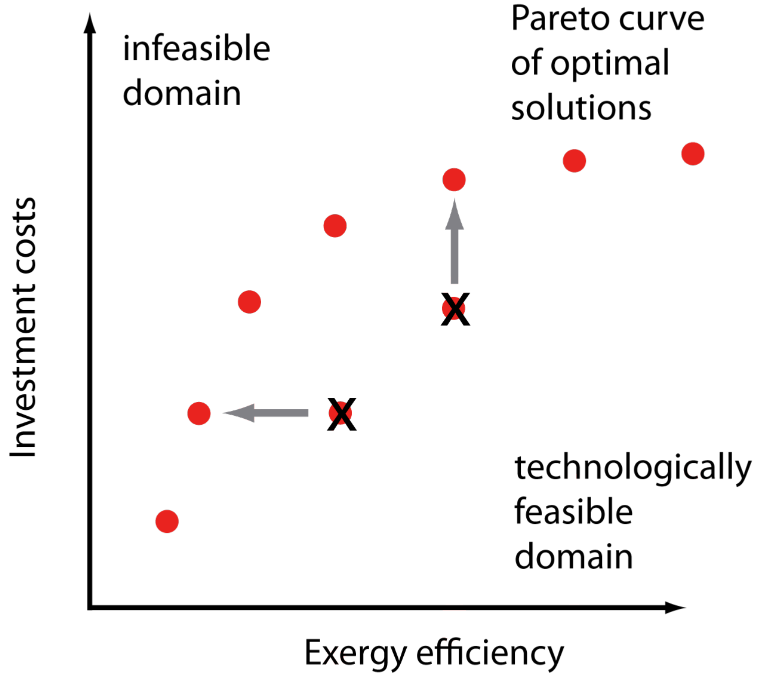
- From literature(1) and thermo-economic models:



(1): Frick, S. et al. «Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs», *Energy*, 35, pp. 2281-2294, 2010

Multi-Objective Optimization

- Calculate trade-off & identify optimal configurations



For each conversion technology:

1) min. investment costs:

$$C_{inv} = C_{i,EGS}(z) + \sum_{w=1}^{n_w} max(C_{i,w,p}(z, r_{DH}), x_d)_{n_p} + C_{i,DH}(r_{DH})$$

2) max. annual profits:

$$P_{an} = \sum_{p=1}^{n_p} t_p \cdot (c_{e^-} \cdot \dot{E}_p^-(z, r_{DH}, x_d) + c_{q^-} \cdot \dot{Q}_p^-(r_{DH}) - c_{o,EGS}(z) - \sum_{w}^{n_w} c_{o,w}(z, r_{DH}, x_d))$$

3) max. system exergy efficiency:

$$\eta = \frac{\sum_{p=1}^{n_p} t_p \cdot (\dot{E}_p^-(z, r_{DH}, x_d) + \dot{Q}_p^-(r_{DH}) \cdot (1 - \frac{T_a}{T_{DH,lm,p}(z)}))}{\sum_{p=1}^{n_p} t_p \cdot \dot{Q}_{EGS,p}^+(z, x_d) \cdot (1 - \frac{T_a}{T_{EGS,lm,p}(z)})}$$

Decision variables:

- x_d: Temperatures, pressures, splitting fractions (EGS & cycles)
- z: EGS construction depth
- r_{DH}: design size of district heating

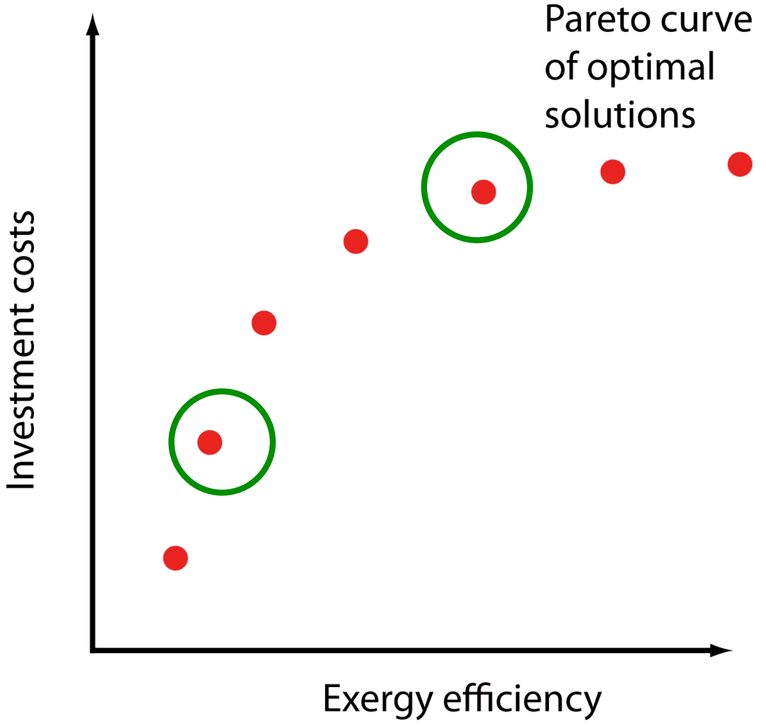
n_w: number of technologies
n_p: number of periods
t_p: operating time of period p
E- : net electricity

Q- : district heating
c_o: operating cost
c_e-: electricity selling cost (0.16 USD/kWh)
c_q-: district heating selling cost (0.11 USD/kWh)

T_a: cold source temperature
T_{lm}: log-mean temperature of hot source

Selection of final optimal configurations

Hundreds of solutions for each Pareto curve!



Best technology at each potential depth (500m step) and DH design size (5MW step)

- *selected on the basis of the payback period:*

$$t_{pb} = \frac{C_{inv,an}}{P_{an}}$$

Lifespan (t_{yr}): 30 years

Interest: 6%

$$E_{CO2,av} = \sum_{p=1}^{n_p} (t_p \cdot (\dot{E}_p^- \cdot e_{CO2,NGCC} + \dot{Q}_p^- \cdot e_{CO2,NGB} - \sum_{i=1}^{n_{eo}} I_{O,i,p})) - (\frac{\sum_{i=1}^{n_{ec}} max(I_{C,i})_{n_p} + \sum_{i=1}^{n_{ee}} max(I_{E,i})_{n_p}}{t_{yr}})$$

Other associated indicators:

- *exergy efficiency*
- *avoided yearly CO2 emissions with IPCC07 (on life cycle basis)*
- *avoided impacts with Ecoindicator99-(h,a) (on life cycle basis)*

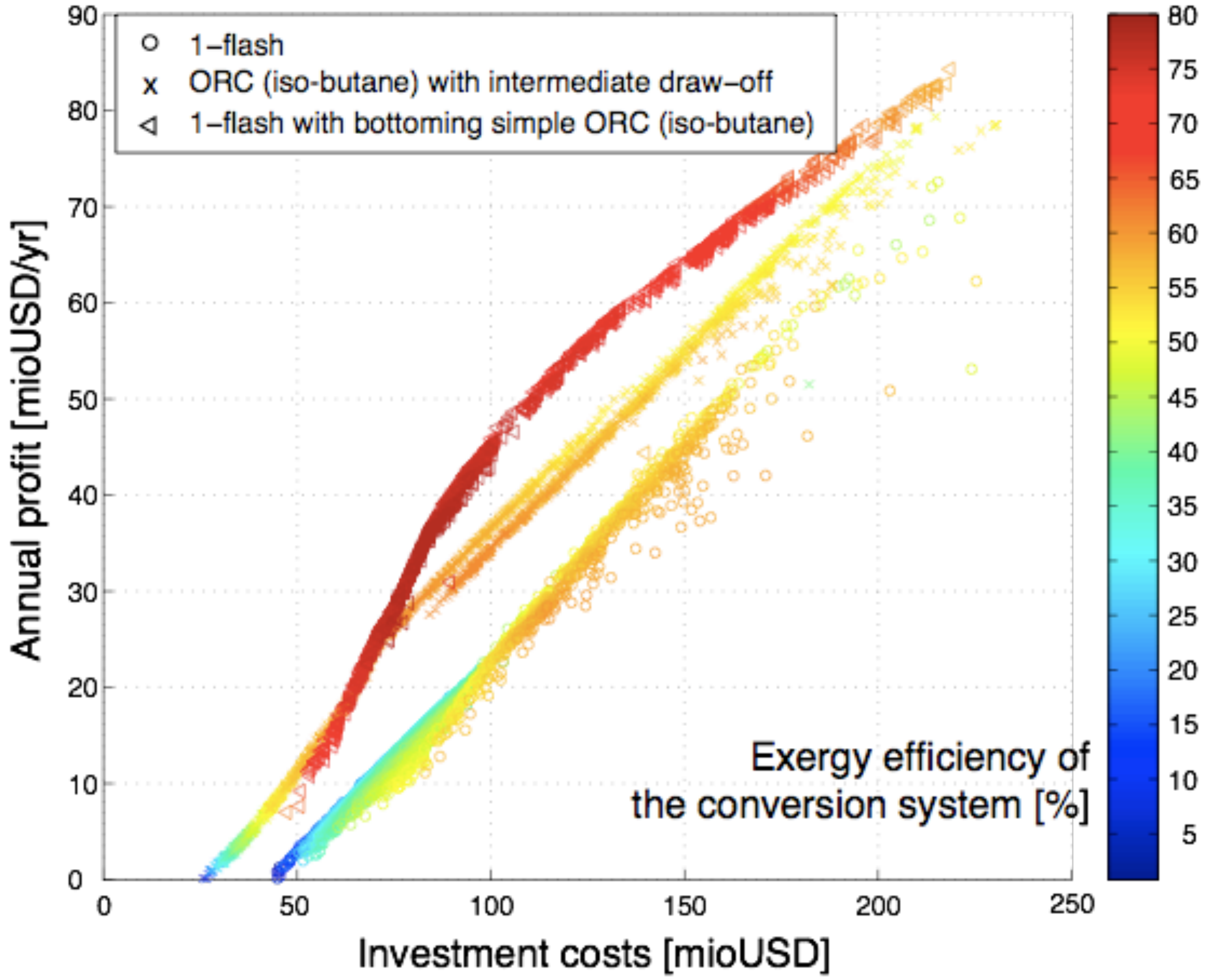
$e_{CO2.NGCC}$: emissions for electricity production with natural gas combined cycle (0.425 kgCO2-eq/kWh)

$e_{CO2.NGB}$: emissions for DH production with natural gas boiler (0.241 kgCO2-eq/kWh)

$I_{C/O/E.i}$: impact associated with construction/operation/end-of-life of element i of life cycle inventory

Examples of Pareto curves

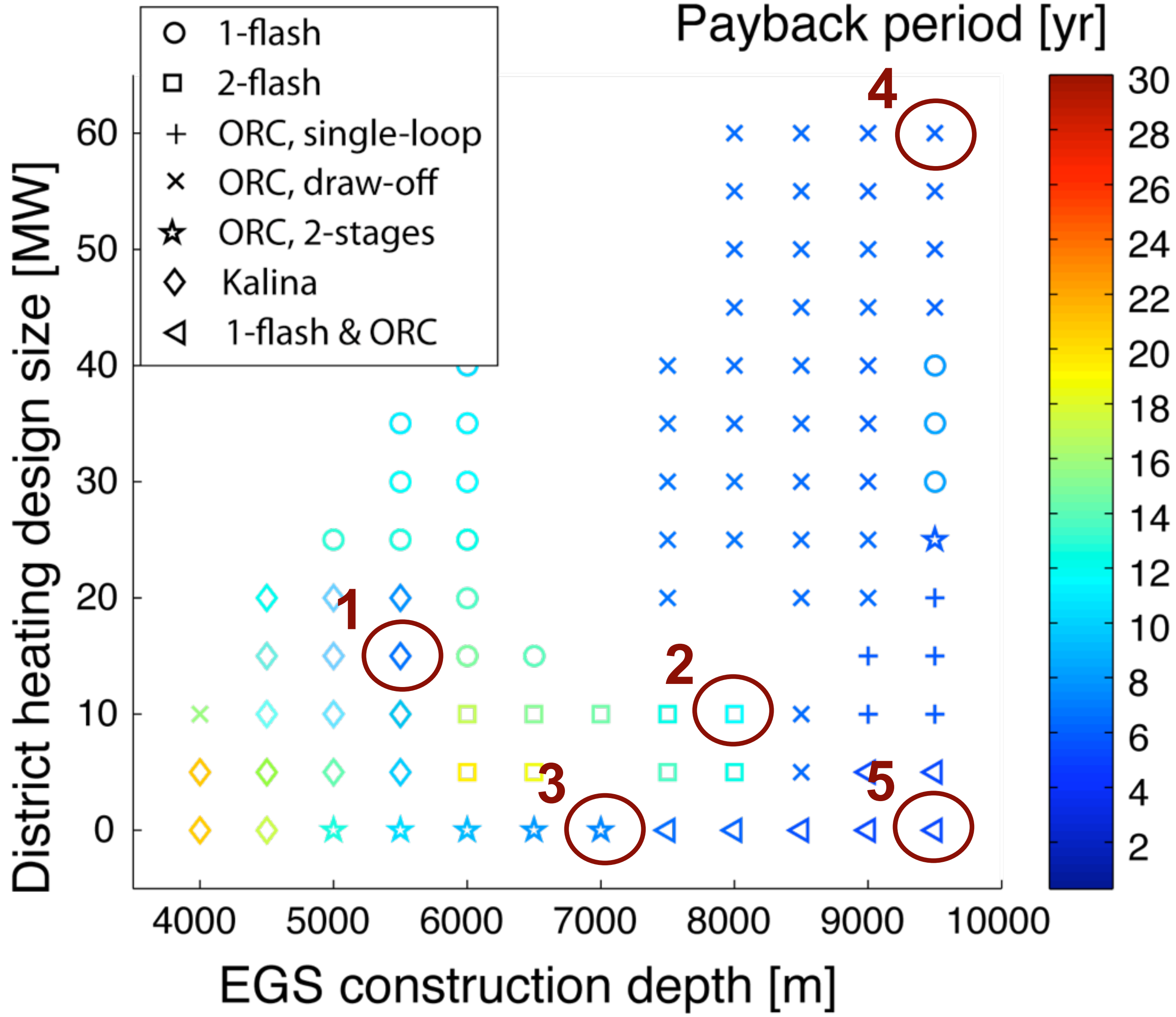
- Trade-offs between 3 objectives:



- *Pareto curves for other technologies show similar behavior*

Final optimal configurations

- Payback period (< 30 years)

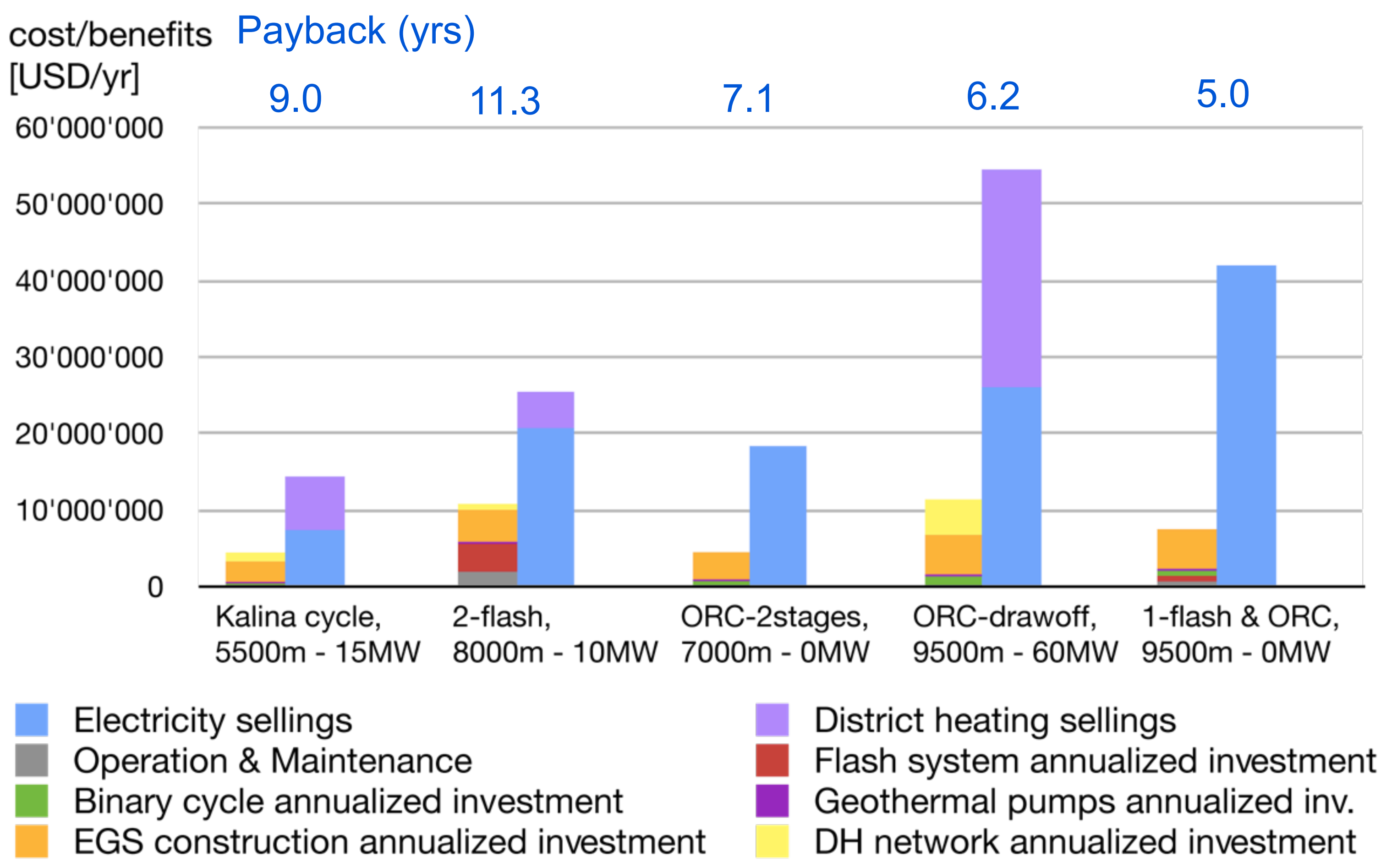


- Payback period tends to decrease with depth
- Effects of cogeneration
  - Decreases payback in lowest range of depths (Kalina)
  - No significant penalty for deep systems
- Best technology is function of depth & DH size

1. low depth & DH → Kalina cycle
2. mid. depth & DH → Flash systems
3. mid. depth & no DH → ORC, 2-stages
4. large depth & DH → ORC, draw-off
5. large depth & no DH → 1-flash, & bottoming ORC, single-loop

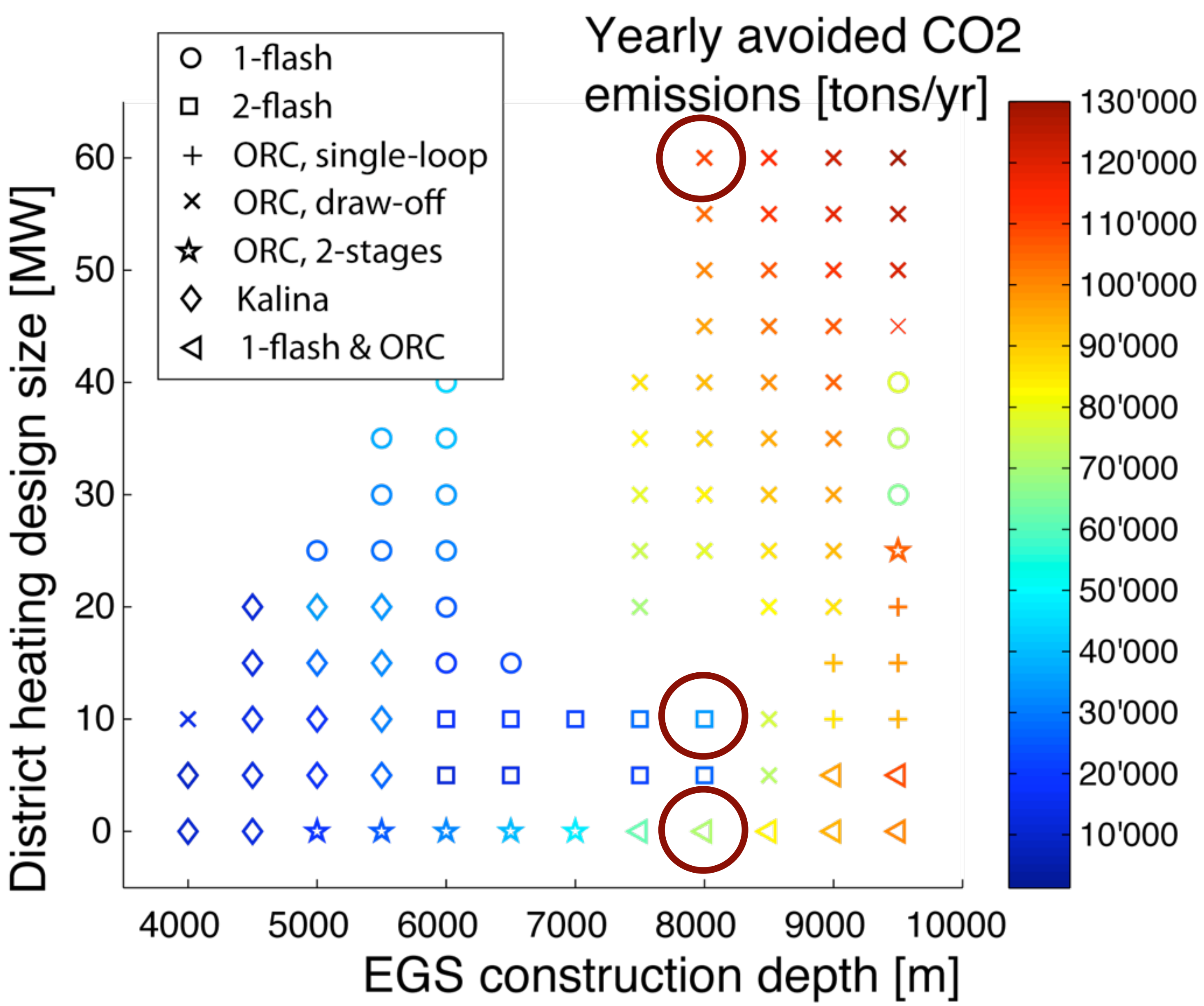
Detailed cost-benefit analysis

- 5 typical configurations



- Costs dominated by
  - EGS construction investment
  - DH network investment
- Efficient system design compensates higher investment
  - Deeper EGS
  - Larger DH systems
- Potentially sensitive to:
  - Geological conditions
  - Drilling costs
  - Energy services prices

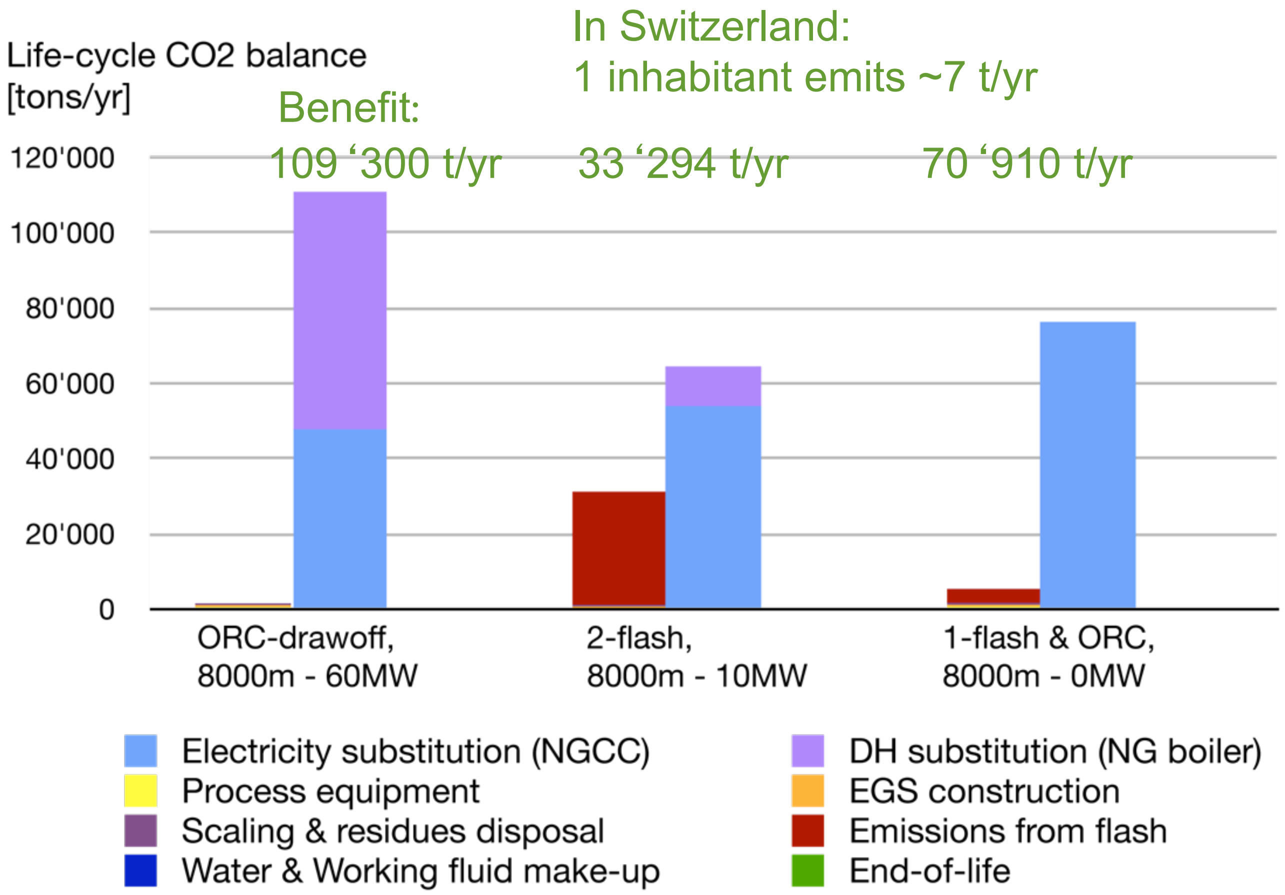
Associated avoided CO_2 emissions



- Beneficial CO_2 balance for all optimal economic configurations
  - Increase with depth due to increased efficiency
- Fossil CO_2 emissions for flash systems decrease performance
  - Effect mitigated by increased efficiency & use of bottoming ORC
  - Favors large DH systems using ORC with intermediate draw-off

Detailed CO_2 balance

- 3 typical configurations



In Switzerland:
1 inhabitant emits ~7 t/yr

Benefit:
109 ‘300 t/yr 33 ‘294 t/yr 70 ‘910 t/yr

◉ Potentially sensitive to:

- Geological conditions
- Substituted services (electricity mix!)

- Efficient system design mitigates impacts from construction
- If emissions from EGS & flash comparable to hydrothermal:
  - potentially not insignificant...
- 1-flash & bottoming ORC
  - reduces size of flash, thus emissions
  - increases avoided impacts from electricity
- CO_2 balance linked with energy efficiency
  - Though electricity avoids more CO2 than DH per kWh (0.425 kg vs 0.241 kg)
  - Favors cogeneration over single electricity production

Conclusions

- Methodology for conceptual design of geothermal energy conversion systems combining thermo-economic optimization and LCA
  - Identify promising configurations
  - Orientate decision-making

- Determination of optimal EGS depths, technologies and DH size for average conditions of Switzerland
  - Selection of technology depends on EGS depth and DH size
  - Environomic performances increase with depth
  - Beneficial environmental balance for all economic optimal configurations
  - Interest of cogeneration
    - Does not penalize economic performances
    - Improves avoided CO_2 emissions

Perspectives

- Inclusion of economic and geological uncertainties in economic & LCA model
  - Drilling costs and technology
  - Energy services prices and avoided impacts
    - Importance of political decisions !
  - Effects of EGS construction depth
    - Reservoir enhancement ?
    - Expected mass flow rate ?
- Necessity to include data of future EGS to be built in models
  - Collaboration between geologists, energy systems engineers & environmental scientists

Thank you for your attention!

Questions?

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