System integration and conceptual framework for the CHPM plant

Árni Ragnarsson, Gunnar Thorgilsson and Vigdís Hardardóttir
ÍSOR – Iceland GeoSurvey

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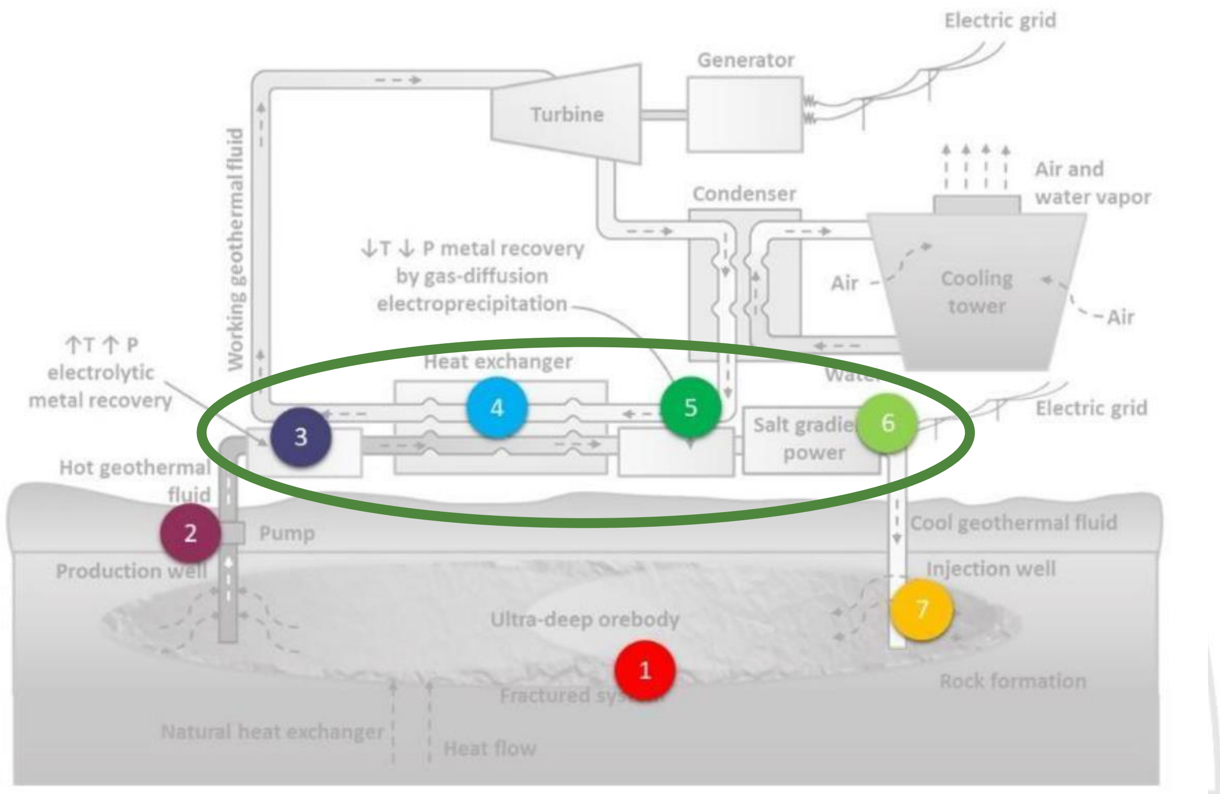
Objectives of the system integration

- Integrate downstream and upstream processes into a single system and develop optimisation strategies for energy and metals production

Technical components identified



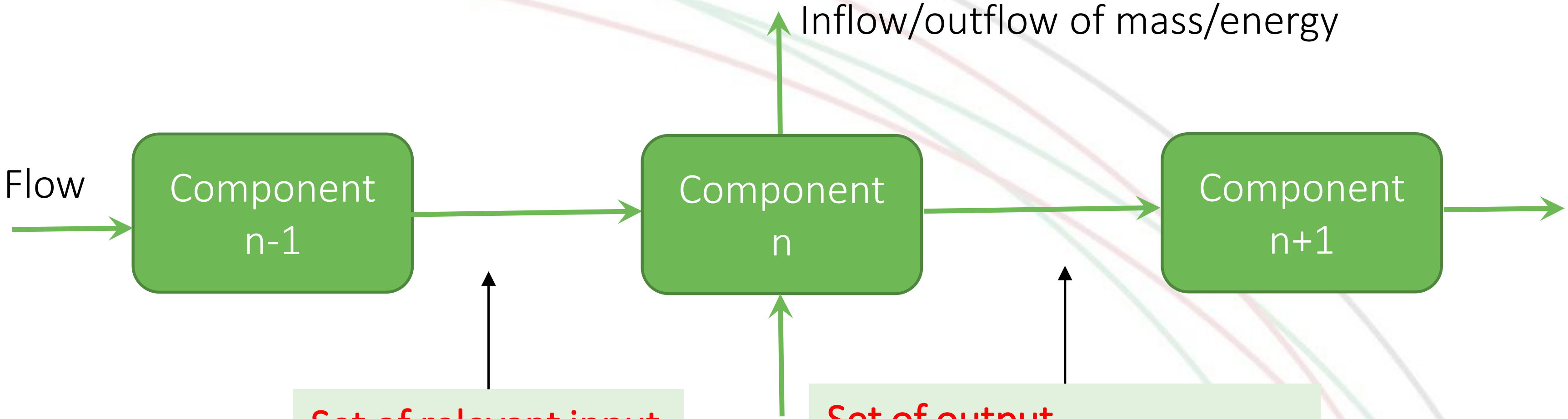
Conceptual framework for CHPM power plant

- Dealing with fluids with high concentration of metals.
- Want to combine metal extraction from the fluid with energy production, both power generation in a conventional binary power plant and direct heat uses of the geothermal energy
- In the system integration we convert outputs of the project work on individual metal extraction and power generation components into an overall architecture design of the envisioned CHPM facility.
- Create a model framework based on component level models which enables linking downstream and upstream geothermal engineering subsystems.

Approach

- Develop a mathematical model of the overall system, including all main components.
- The overall model is made up of elements or sub-models describing the behaviour of each component (component models).
- A set of design parameters for the overall system is defined.
- For each component within the system a mathematical description of what happens within the component is developed.
- Each component has an input from the previous component in the chain and an output that will feed the following component.
- The overall simulation is used to study different scenarios and perform sensitivity analysis.

Component model



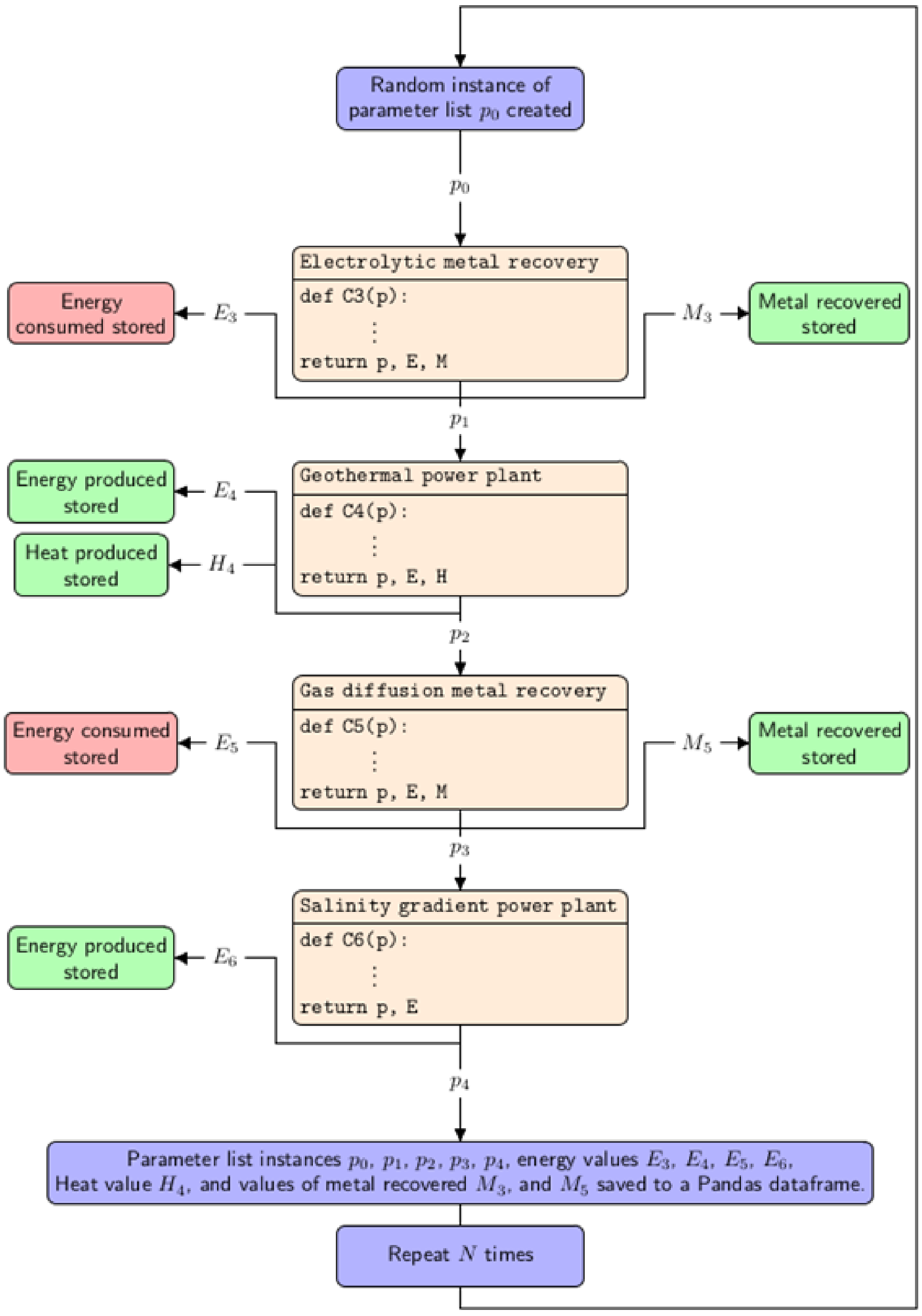
Set of relevant input parameters (A_n):

T: temperature
P: pressure
m: flow rate
M: concentration
S: salinity
etc.

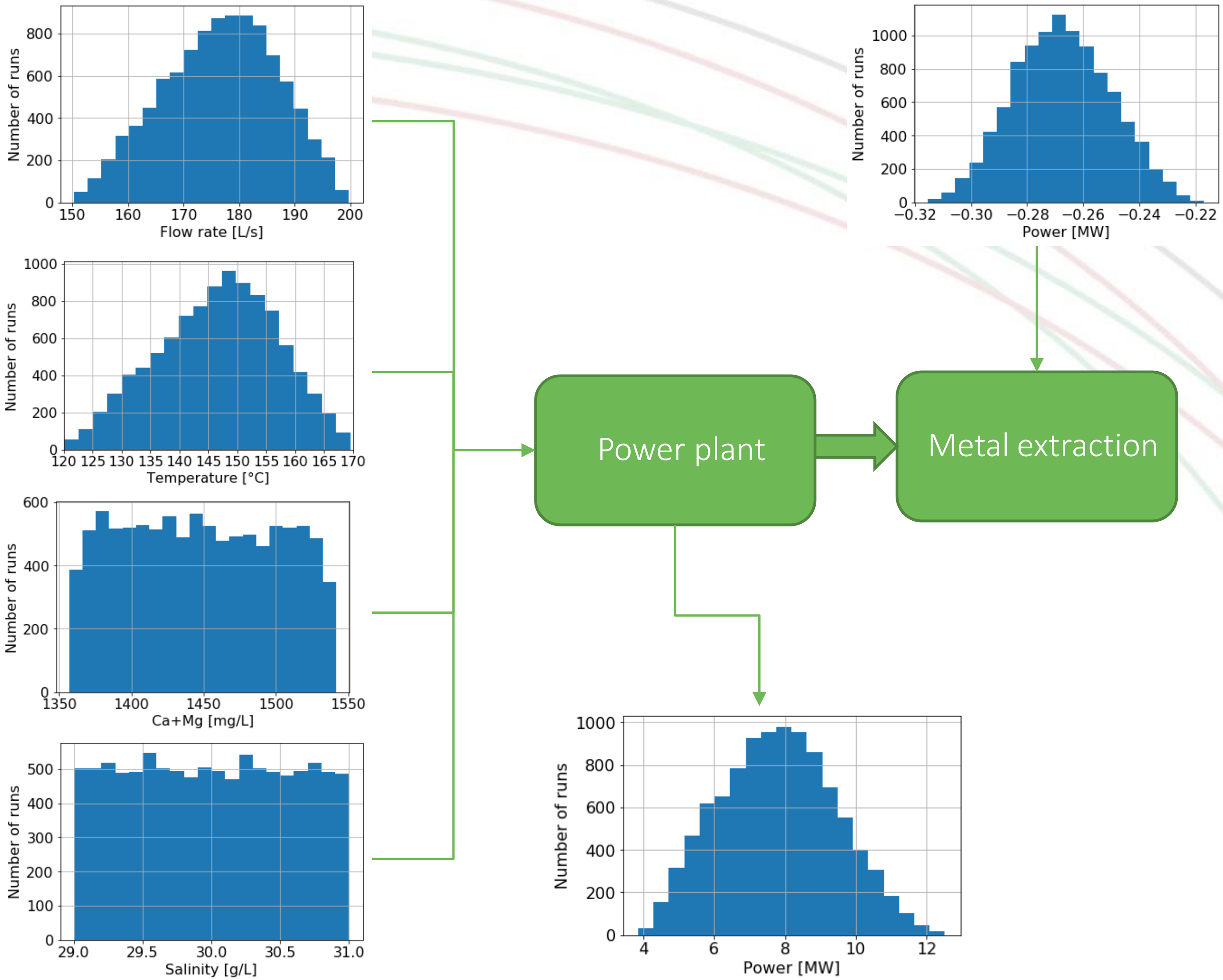
Set of output parameters A_{n+1} = f (A_n)

f is a function that describes the relationsship between the input and output parameters of component n

Schematics of the Monte Carlo model



Examples of Monte Carlo modelling

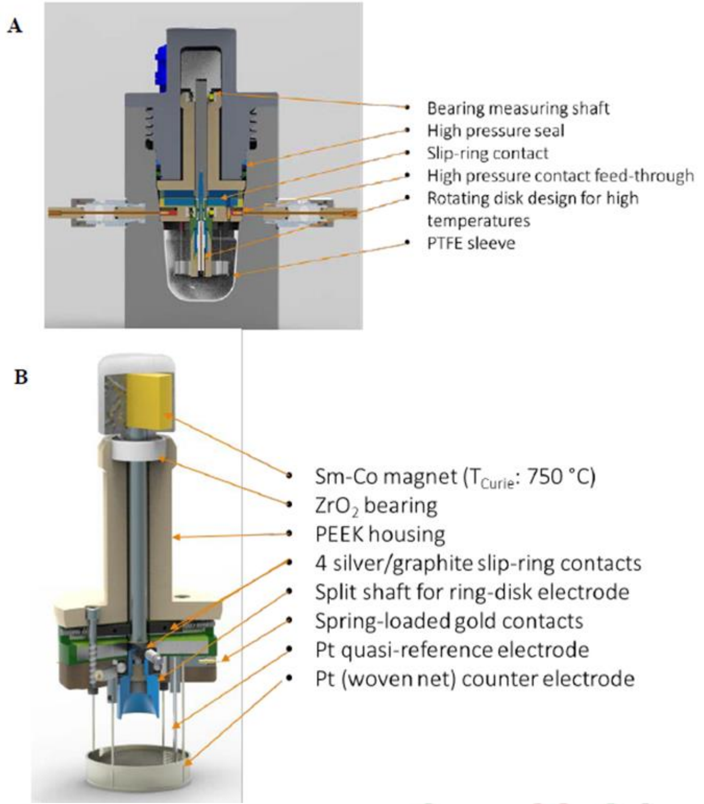


Reservoir and production/reinjection wells

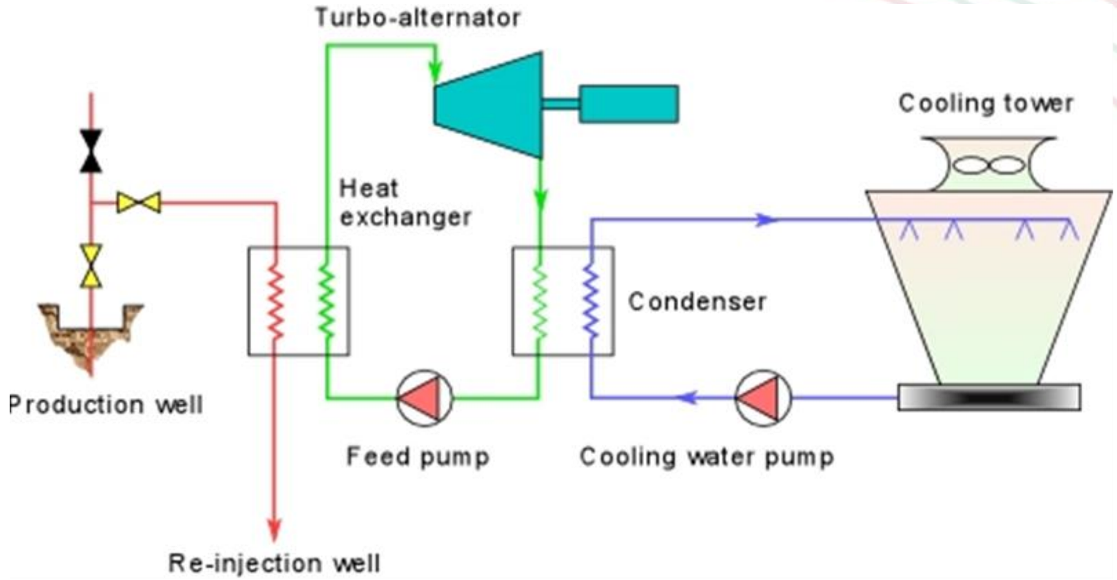
- In principle, the geothermal reservoir as well as the production and reinjection wells are components that could be described mathematically in a similar way as other components in the system.
- The current system model does not include separate models for these components, but only the surface components.
- The main reason for this is the complexity of these components. They can be added in further studies if desired.
- The current system model uses fluid properties at the production wellhead as input. These are based on reservoir properties from known geothermal fields.

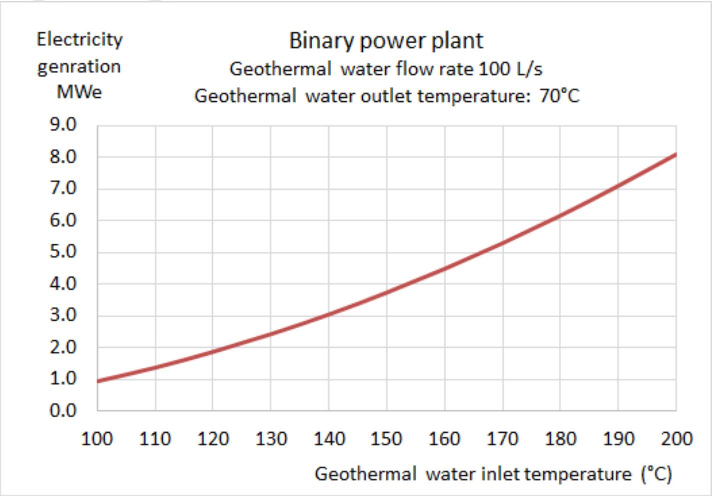
Electrolytic metal recovery

- Uses electrochemical reactions to deposit metals
- Designed to perform at high temperatures and high pressures up to 200 bar and 300°C
- Experiments performed in small batch reactors
- The electrolytic metal deposition technology is implemented in a flow-through reactor that can be readily integrated in a geothermal loop with a high throughput (150 m^3/h or more).

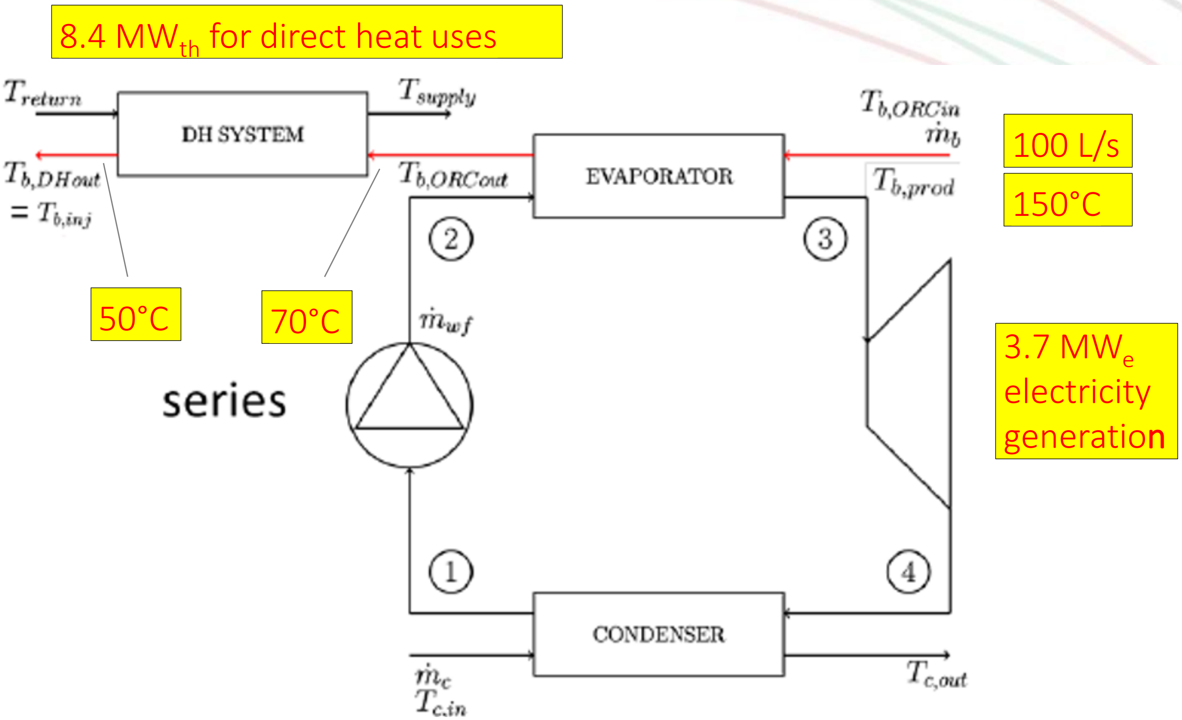


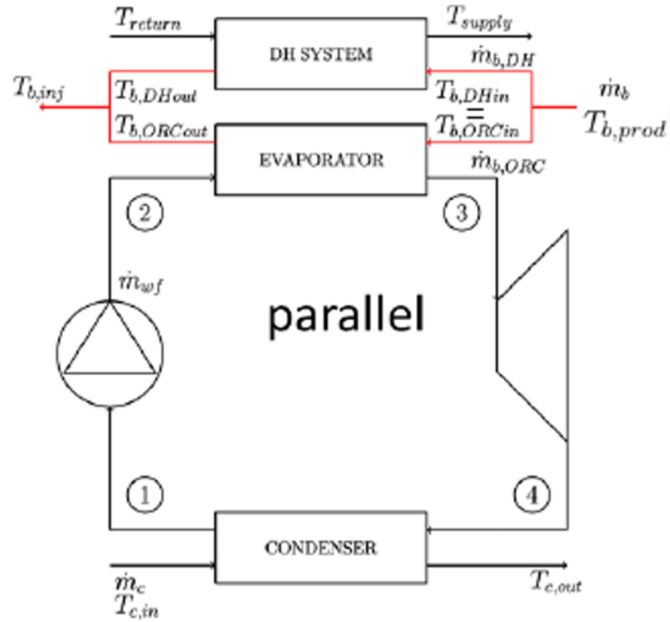
Binary power plant





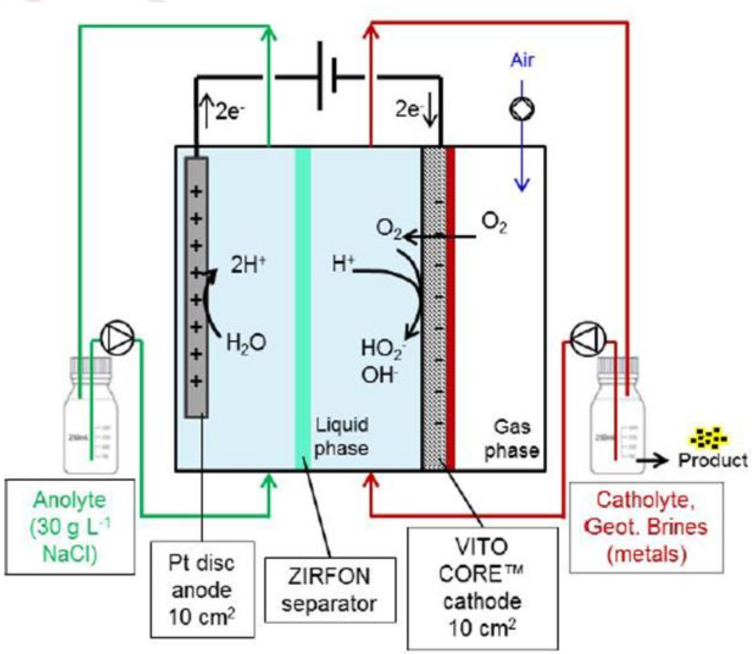
Combined heat and power generation (CHP)





Gas diffusion electro-precipitation and electro-crystallisation

- The GDEx can remove metal and metalloid ions from an aqueous solution, transforming them into an amorphous or crystalline (nano) precipitate which can be easily recovered by sedimentation.
- The process uses porous activated carbon-based gas-diffusion electrodes, through which an oxidant gas is passed.



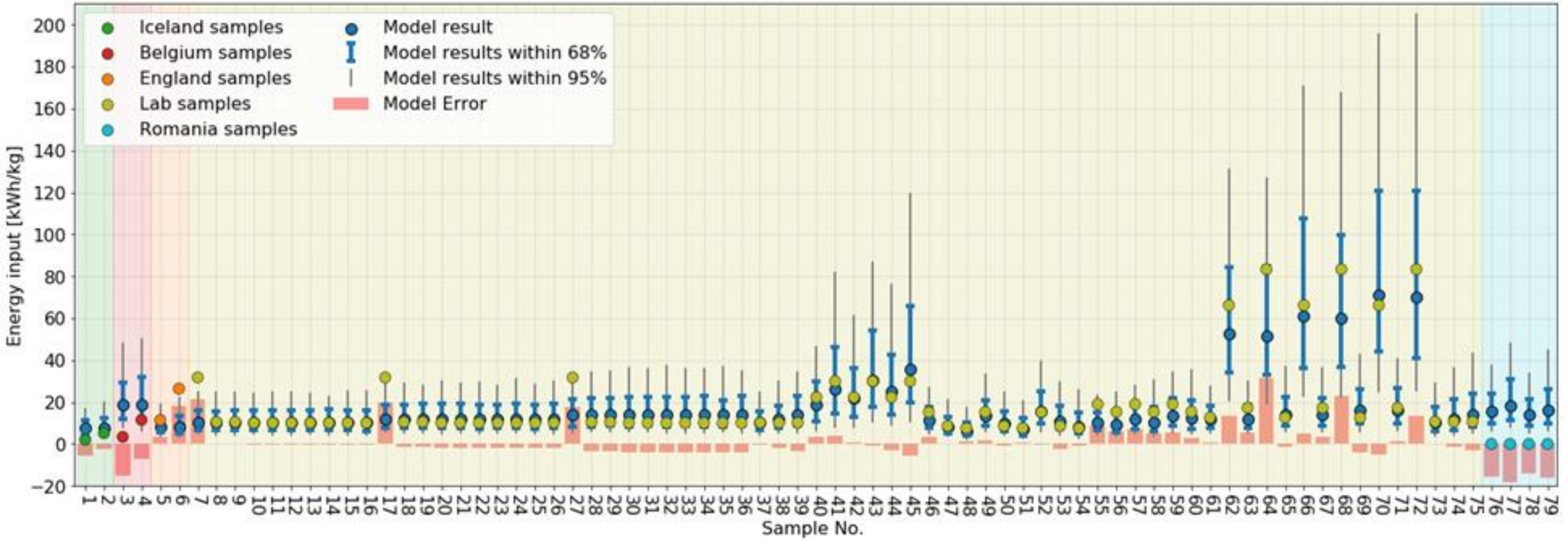
Modelling of the GDEx component (1)

- Based on the results of laboratory measurements of the energy usage and ratios of recovered metals from brine for different values of Mg and Ca concentrations, salinity (S), working electrode potential (Ewe), temperature (T), and Ph.
- Most samples simulated with emphasis on studying Li and Al recovery for different parameters and brine compositions.
- The energy input used per kg of recovered metals and ratios of metal recovery are modelled via linear regression analysis using the StatsModel package in Python.
- The resulting model is described by the following equation:

  E_{inn}=exp(A + B·Mg + C·Ca + D·Ph + E·S + F·T + G·Ewe)

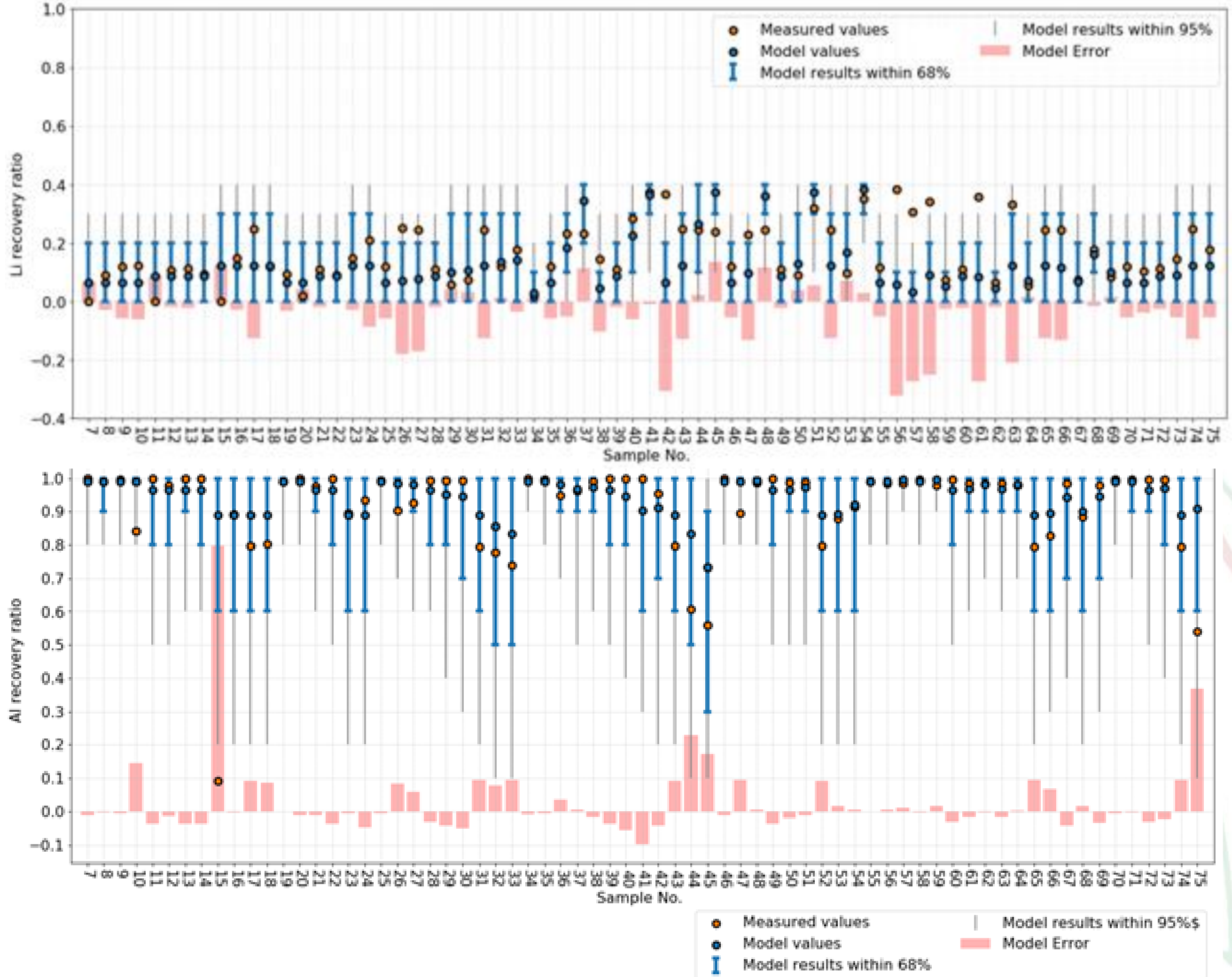
  where A, B, C, D, E, F, and G are the model parameters that are estimated from the regression analysis.

Modelling of the GDEx component (2)



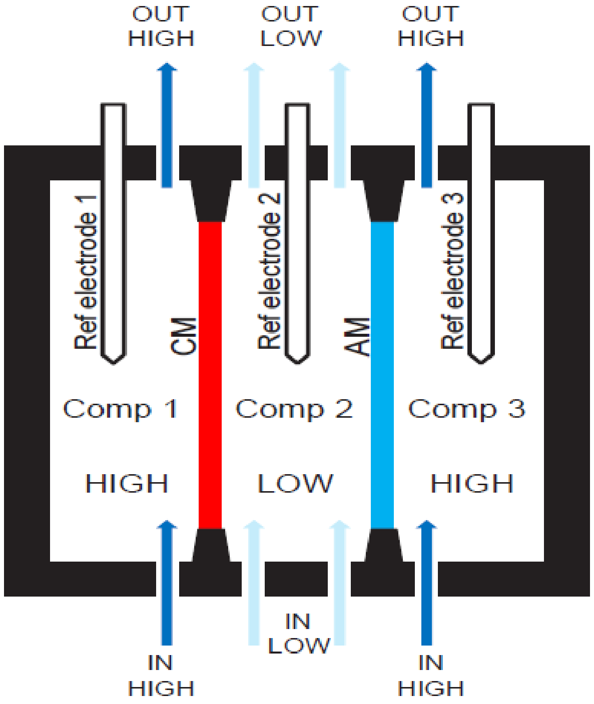
- The flow rate of the experiments that are used to calibrate the model was 40 ml/min or around 6.6×10^{-4} L/s. The flow that a typical geothermal power plant consumes can be five orders of magnitude larger (100 L/s). Therefore, the experimental results are extrapolated linearly by a factor in the order of magnitude of 10^5 in the system model.

Modelling of the GDEx component (3)



Salt gradient power (1)

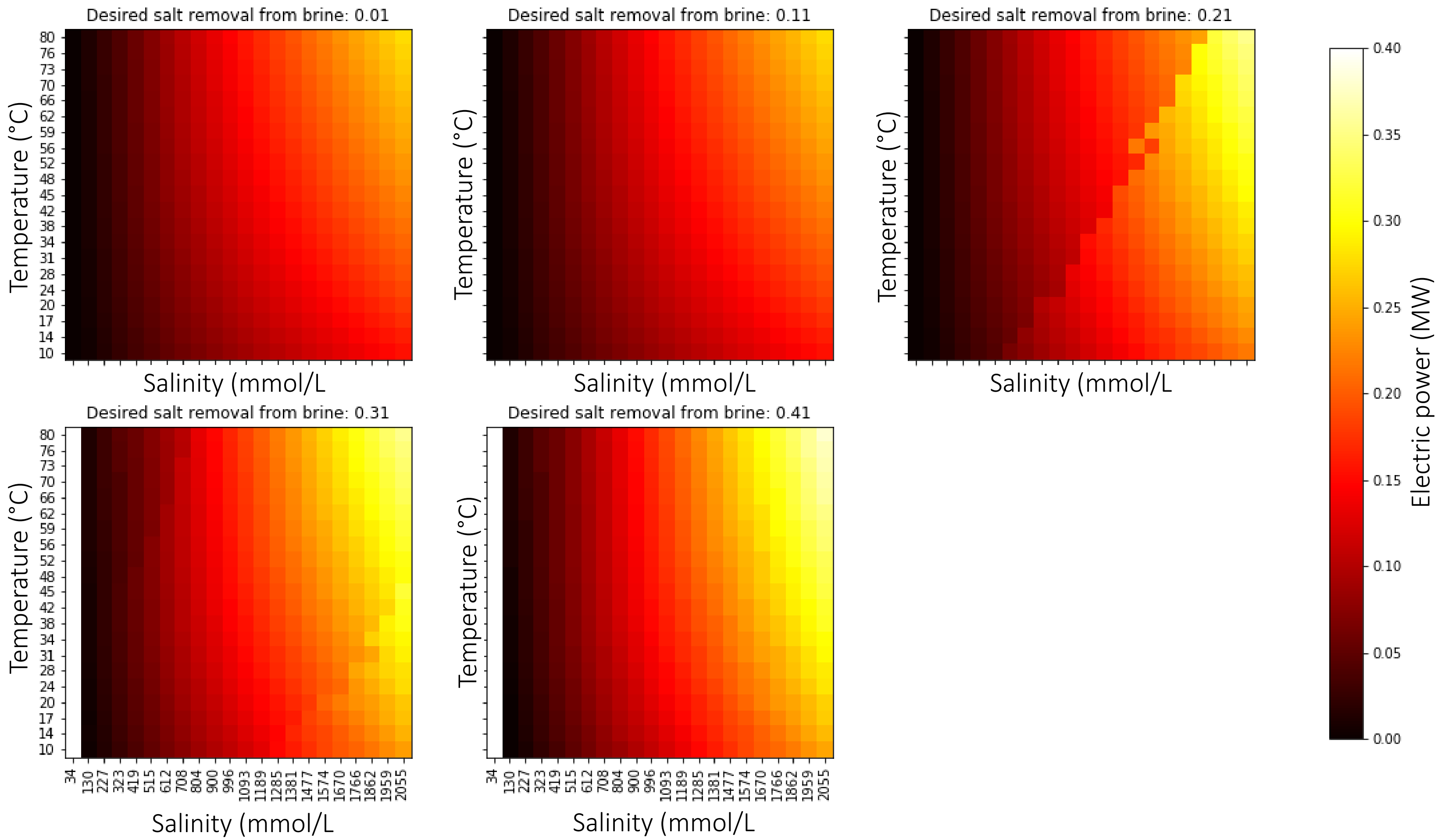
- The reverse Salt Gradient component is composed of compartments separated by Cation exchange Membrane (CM) and Anion exchange Membranes (AM).
- Through these compartments brine solution (HIGH) and low salinity solution (LOW) flow.
- The concentration gradients across the membranes cause the ions (Na+ and Cl-) to move in opposite directions, thus creating potential difference.



Salt gradient power (2)

- Salt Gradient Power (SGP) technology consists of extraction of the "osmotic energy" from two salt solutions with different salt concentration. Constant supply of two water streams with a salinity difference is necessary.
- The model calculates power output, number of stacks in series and total AEM/CEM (anion/cation exchange) membrane surface required at maximal power output.
- The model will calculate a series of stacks according to the required desalination and given the stack length 'l'. For each stack an optimal load will be configured to generate maximum power
- The model then returns some essential values of each stack (outlet concentrations, max power density and effective desalination) and some overall number (e.g. max Power output, total cell pair surface, average power density of all stacks combined) in the dialogue box, e.g.:

Salt gradient power – electricity output

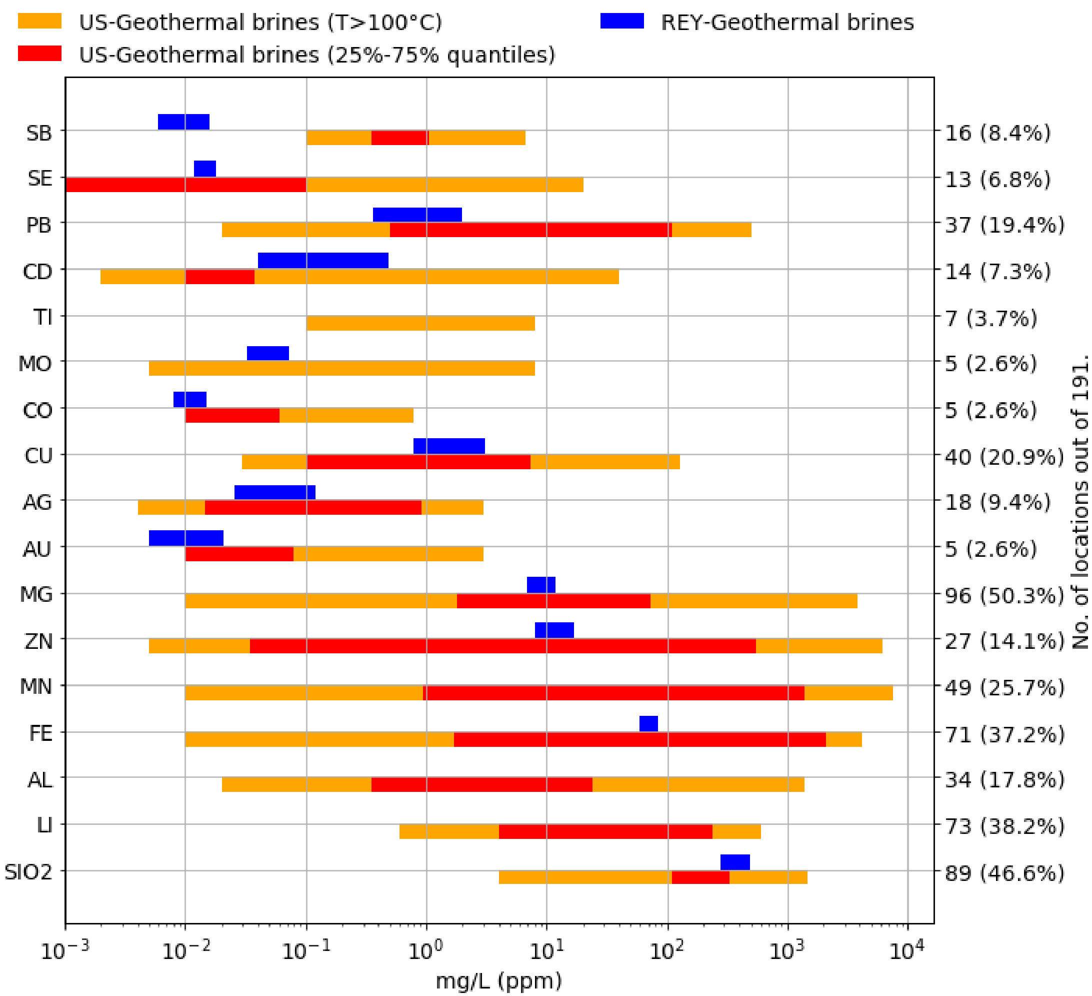


Set of parameters for the integrated system

- Temperature: T [°C]
- Pressure: P [bar]
- Acitity/basitity: pH [-]
- Redox condition: Rd [eH]
- Oxygen fugacity: fO_2 [bar]
- Carbon dioxide: CO_2 [bar]
- Conductivity: si [S/m]

- Flow rate: q [L/s]
- Salinity: S [g/L]
- Oxidizing compounds: O_x [mg/L]
- Concentrated suspended solids: Css [mg/L]

Examples of metal content in geothermal brine



Which metals should we concentrate on?

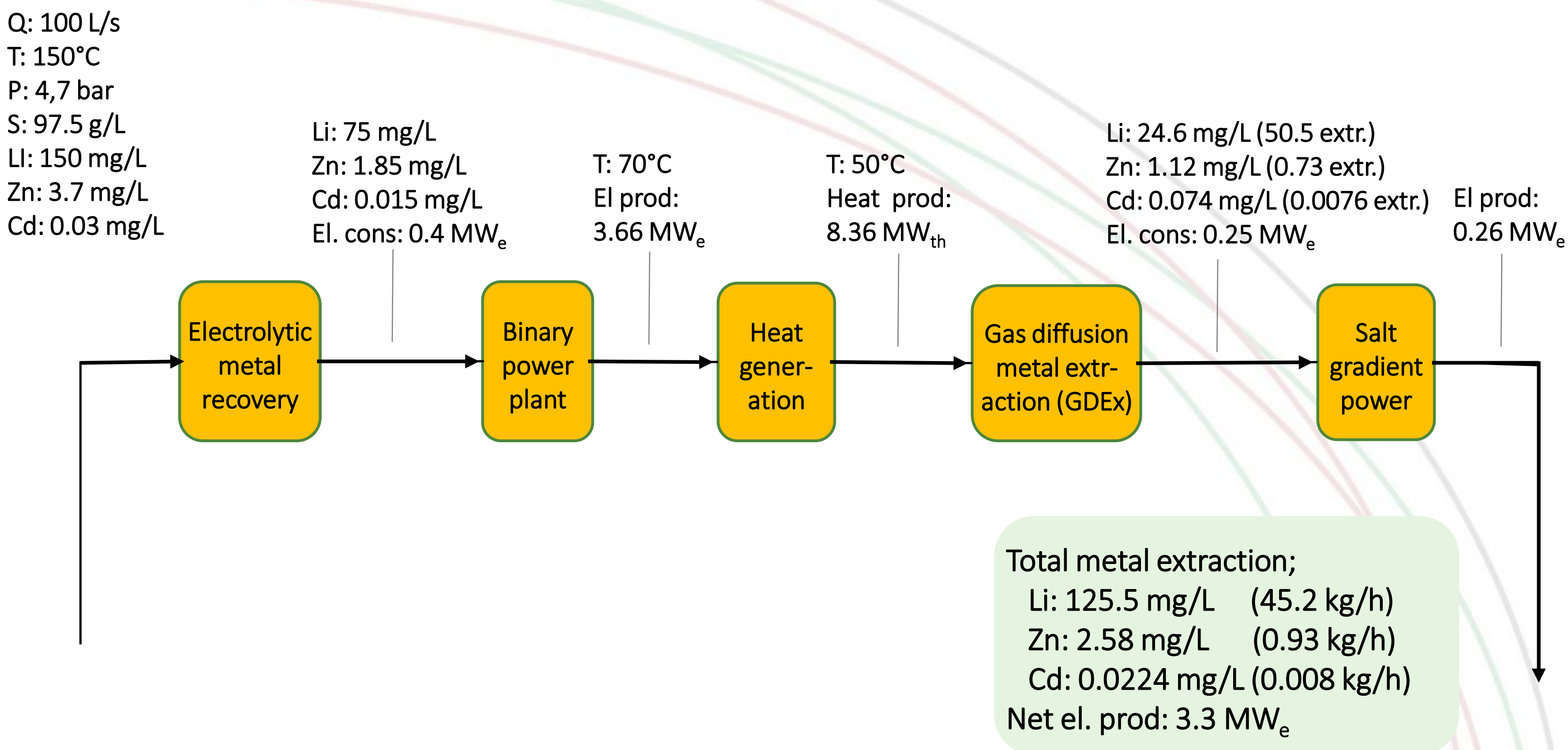
Data from:

G. Neupane and D.S. Wendt, "Assessment of Mineral Resources in Geothermal Brines in the US", *PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University* 2017

M. Hannington et al, "Gold enrichment in active geothermal systems by accumulating colloidal suspensions", *Nature Geoscience* **volume 9**, pages 299–302 (2016)

Demonstration of a possible outcome - Landau

Based on geothermal fluid from Landau, Germany



Demonstration of a possible outcome - Reykjanes

Based on geothermal fluid from Reykjanes, Iceland

Q: 100 L/s
T: 150°C
P: 4,7 bar
S: 35 g/L
LI: 6.55 mg/L
Ag: 0.0676 mg/L
Co: 0.0133 mg/L
Au: 0,0071 mg/L

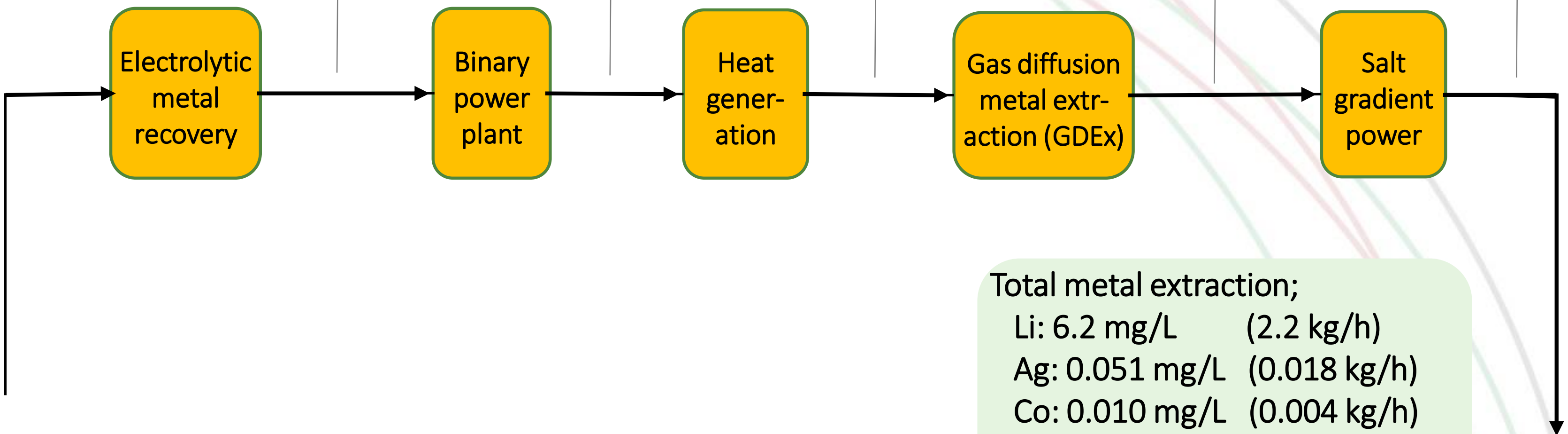
Li: 3.28 mg/L
Ag: 0.0338 mg/l
Co: 0.00665 mg/L
Au: 0.0036 mg/L
El. cons: 0.05 MW_e

T: 70°C
El prod:
3.77 MW_e

T: 50°C
Heat prod:
8.36 MW_{th}

Li: 0.359 mg/L (2.92 extr.)
Ag: 0.0167 mg/L (0.0171 extr.)
Co: mg/L 0.00335 (0.0033 extr.)
Au: 0.00178 mg/L (0.0018 extr.)
El. cons: 0.043 MW_e

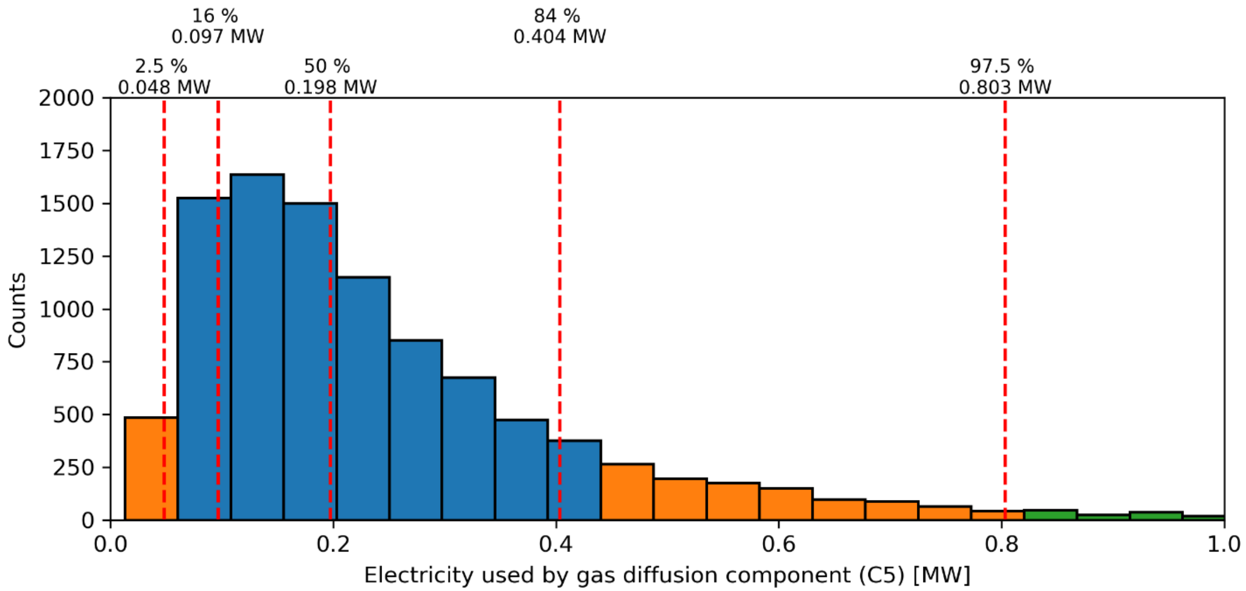
El prod:
0.079 MW_e

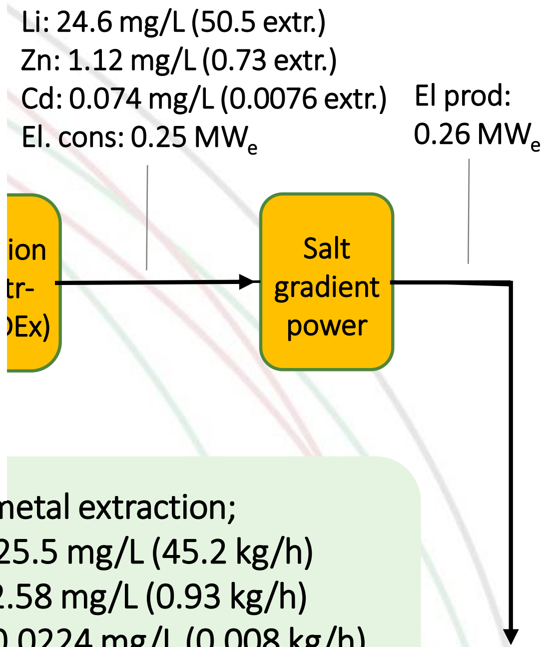


Total metal extraction;
Li: 6.2 mg/L (2.2 kg/h)
Ag: 0.051 mg/L (0.018 kg/h)
Co: 0.010 mg/L (0.004 kg/h)
Au: 0.0054 mg/l (0.002 kg/h)
Net el. prod: 3.8 MW_e

Demonstration of a possible outcome - Landau

Based on geothermal fluid from Landau, Germany





Total metal extraction;

Li: 125.5 mg/L (45.2 kg/h)

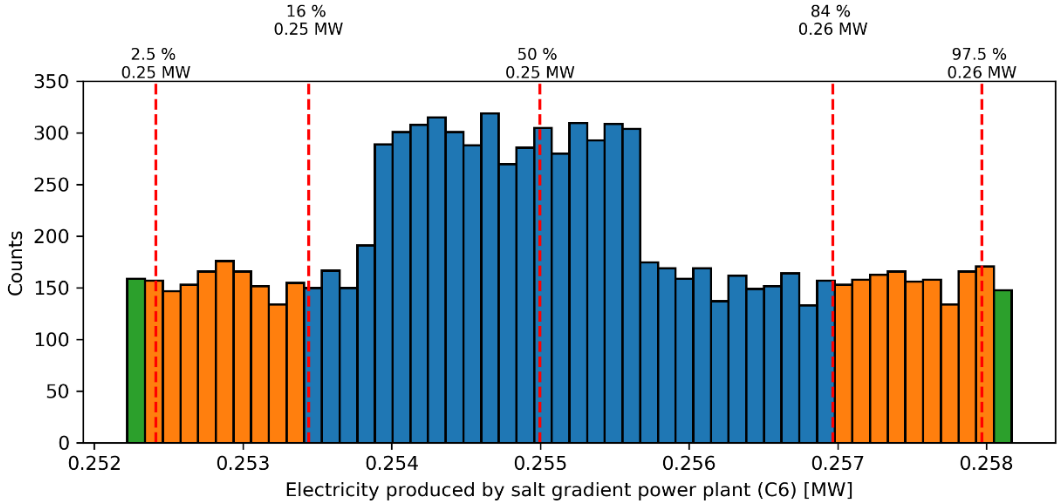
Zn: 2.58 mg/L (0.93 kg/h)

Cd: 0.0224 mg/L (0.008 kg/h)

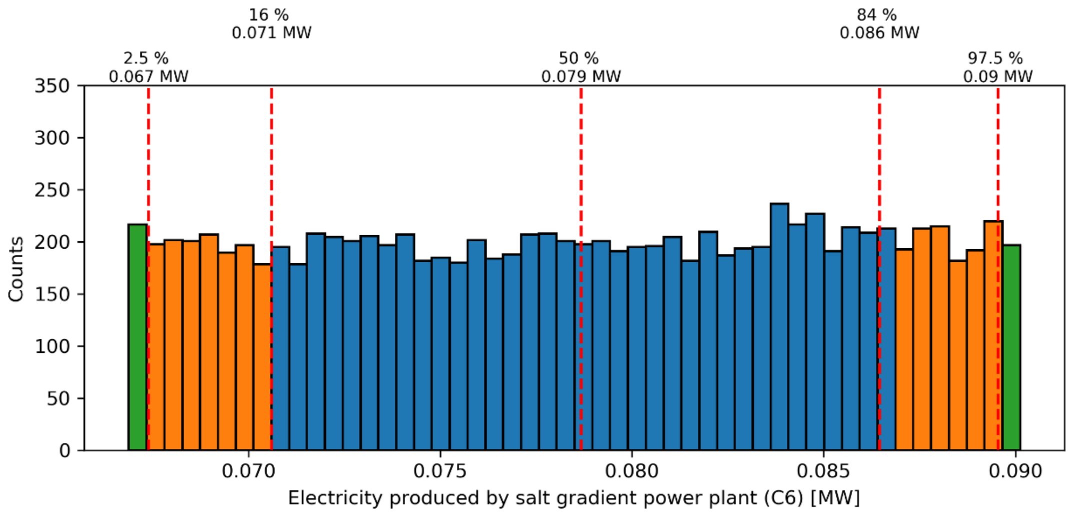
Net el. prod: 3.3 MW_e

Electricity produced by the salt gradient power plant

Landau



Reykjanes



Final remarks

- A system integration model has been developed based on statistical analysis of the system parameters.
- Aim at performing final system integration for the CHPM2030 project based on already selected scenarios and more complete coponent models.
- Sensitivity analysis will be performed.
- Topics for improved system integration in the future:
  - Include a simple reservoir model, leaching agents, well simulator, etc.
  - Study how to upscale results from lab experiments to a pilot plant.
  - Include the market aspect and economic feasibility, e.g. balance between metal and energy production.
  - Etc.


THANK YOU