Environmental risk assessment of enhanced geothermal systems (EGS) incl. seismic risks

Stephan Pfister

68th LCA Forum (DF68) on "LCA of key technologies for future electricity supply"
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Presentation based on collaboration with

- Dr. Kathrin Menberg,
- Prof. Peter Bayer,
- Prof. Philipp Blum:

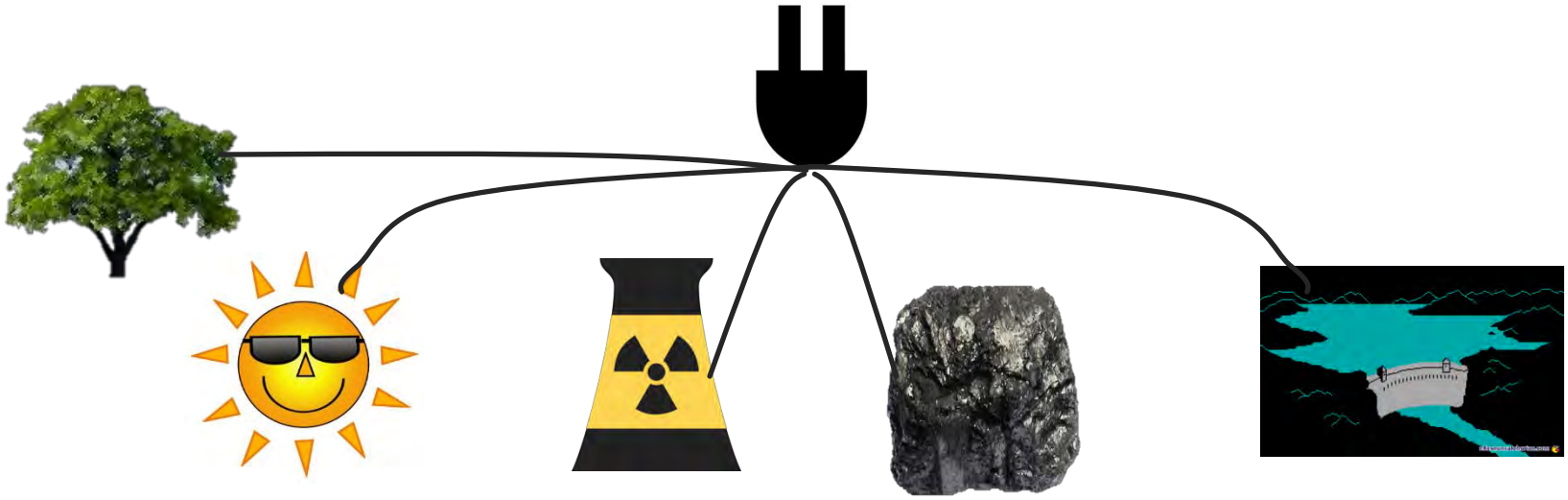
Paper: “A matter of meters: State of the art in the life cycle assessment of enhanced geothermal systems.” Energy and Environmental Science, 9(9).

- Patrick Hädener:

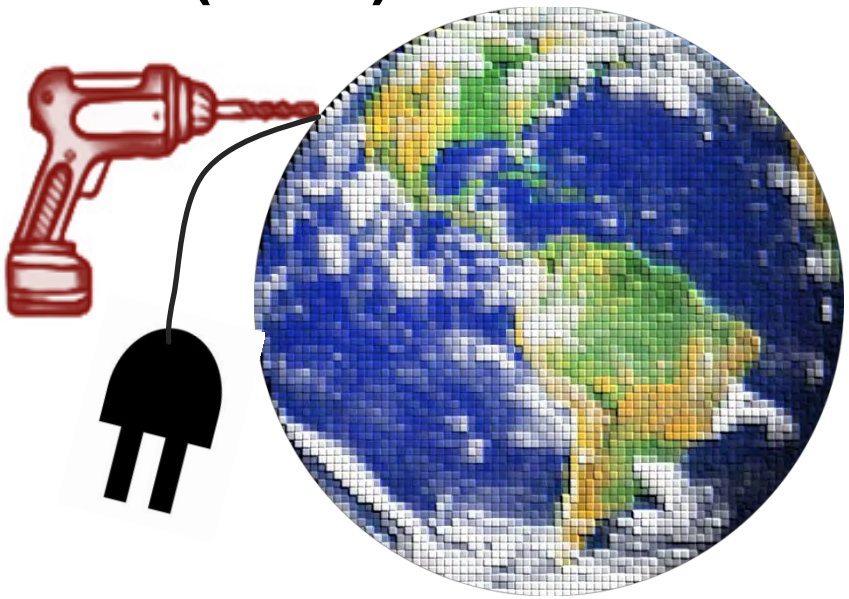
Bachelor Thesis on EGS and seismicity

Future Energy Systems

- Electricity demand is still rising
  - Fossil and nuclear fuels to be outphased
  - Hydropower potential largely utilized
  - PV and Wind: variability problems (+ Swiss conditions not optimal)
  - Biomass potential limited

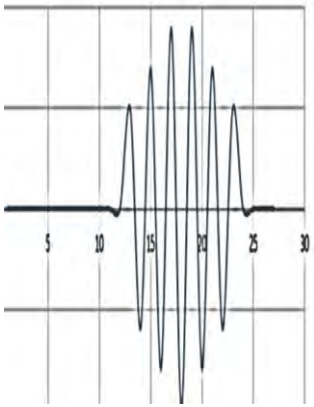


Enhanced Geothermal Systems (EGS)



- Emerging technology
- Very low LCA impacts
- Potential in Switzerland

- Seismicity problem



Geothermal energy (Menberg et al. 2016)

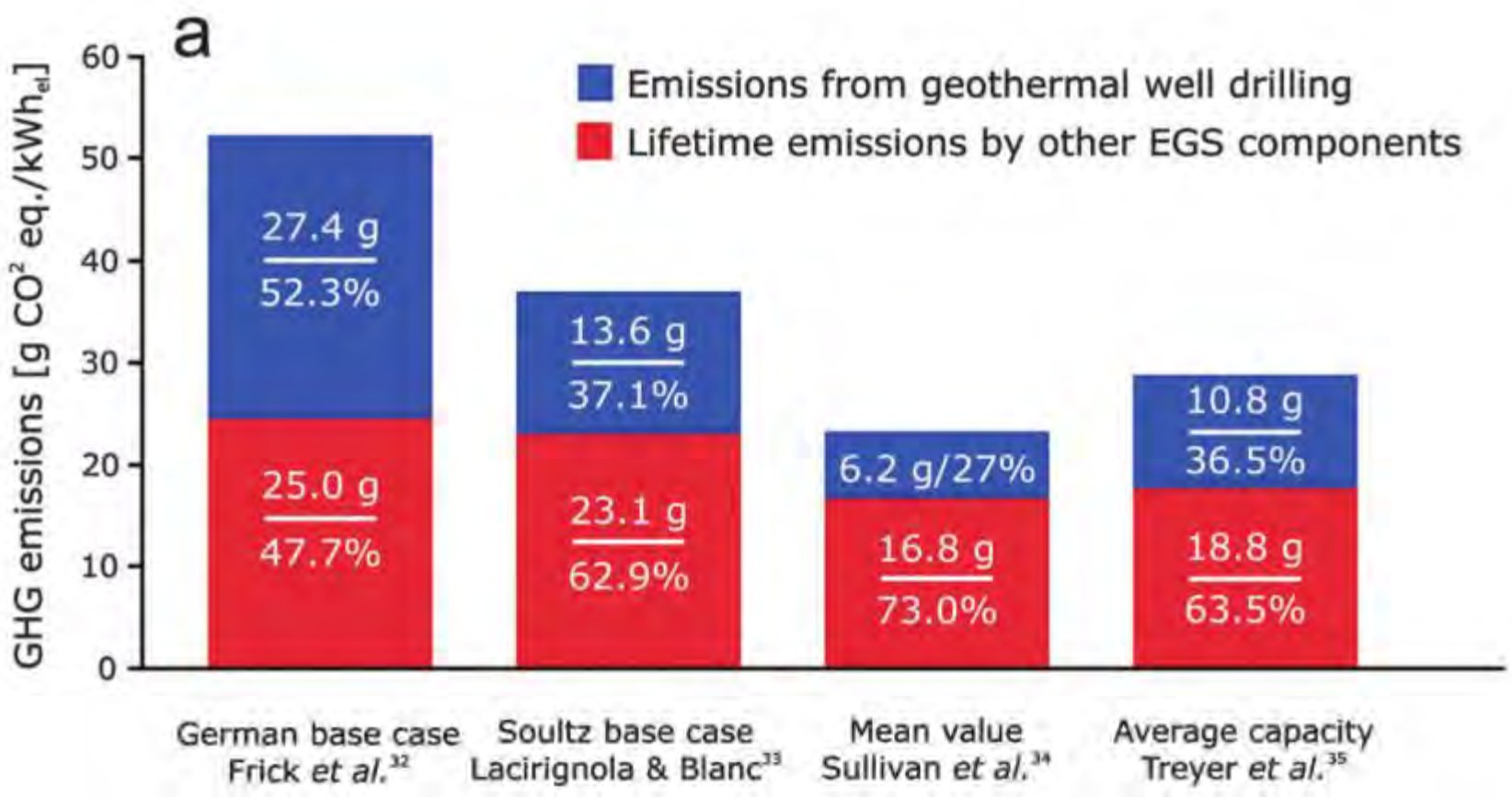
- Literature review of existing studies
  - Integrating model into a single one
  - Borehole drilling most relevant

- Definition of scenarios (incl. learning effects)
  - New drilling technology
  - Co-generation

- Approach:
  - Electric drilling (net energy production approach)
  - Model impact as function of borehole

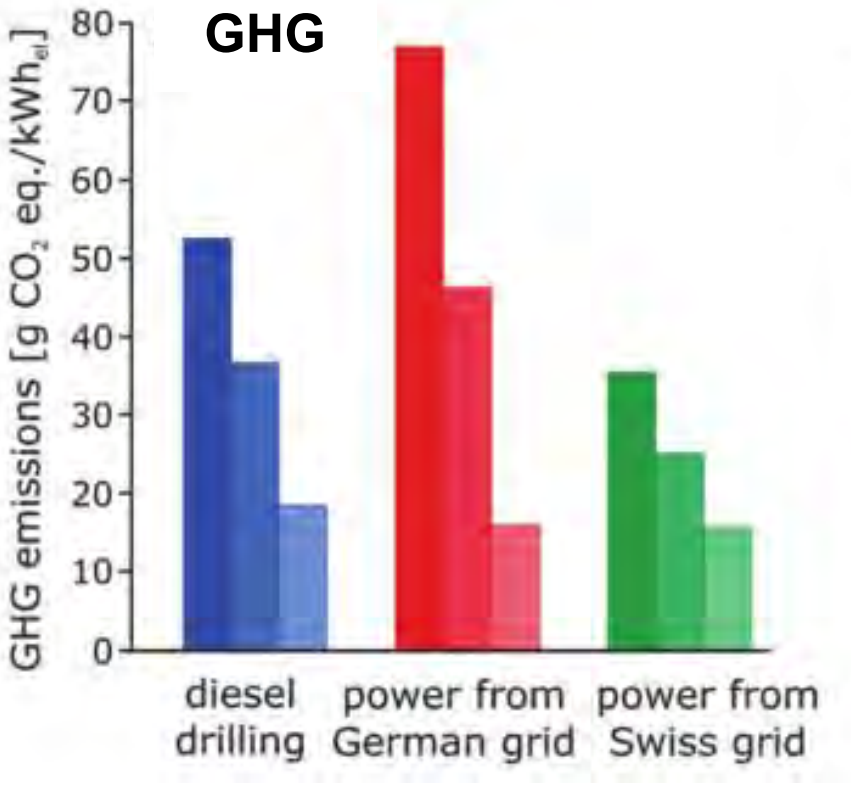
Previous LCA

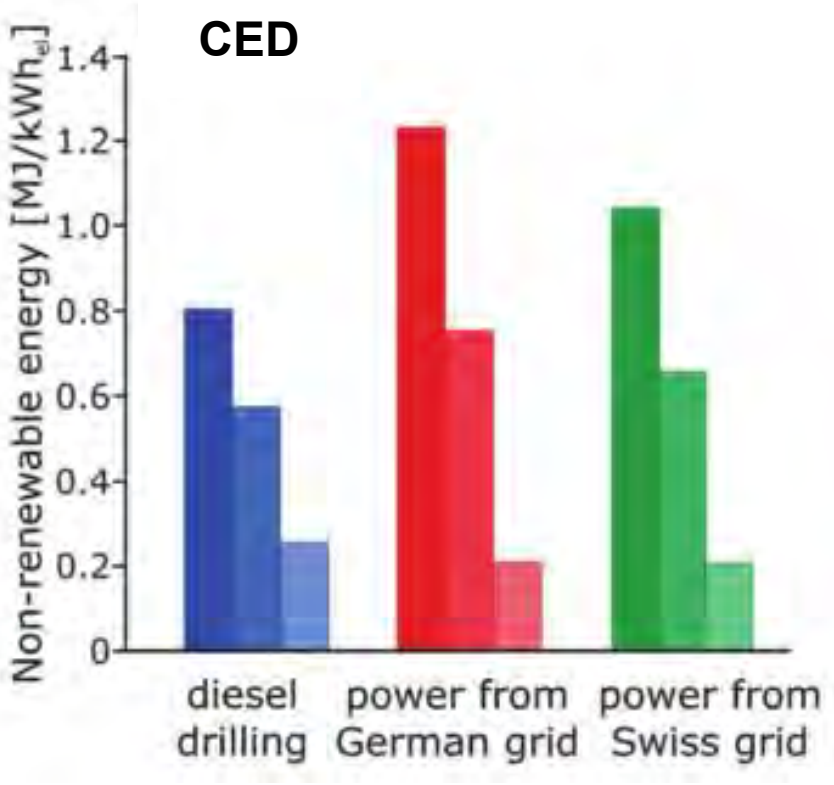
- 25-50% from drilling



Drilling options: diesel, electricity

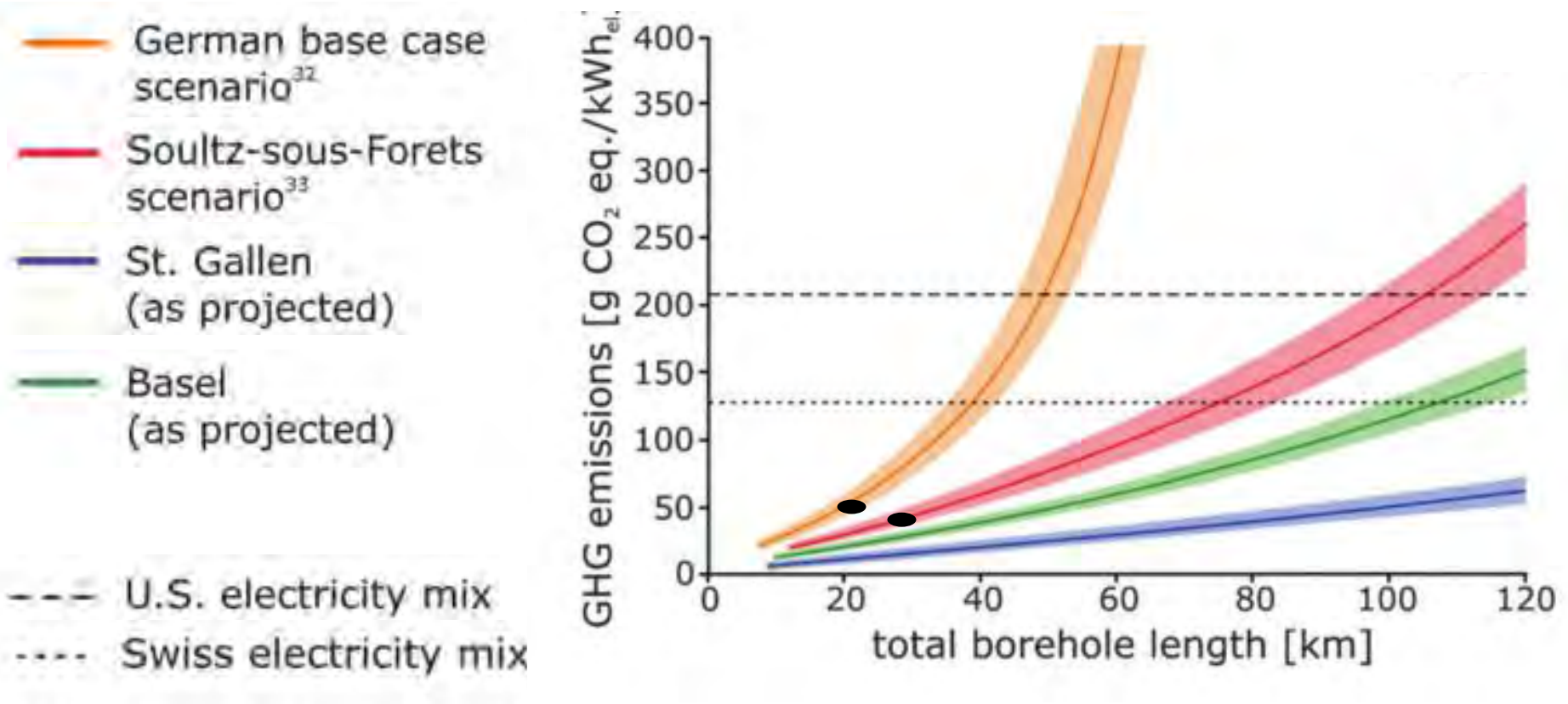
- Impacts for 3 different scenarios



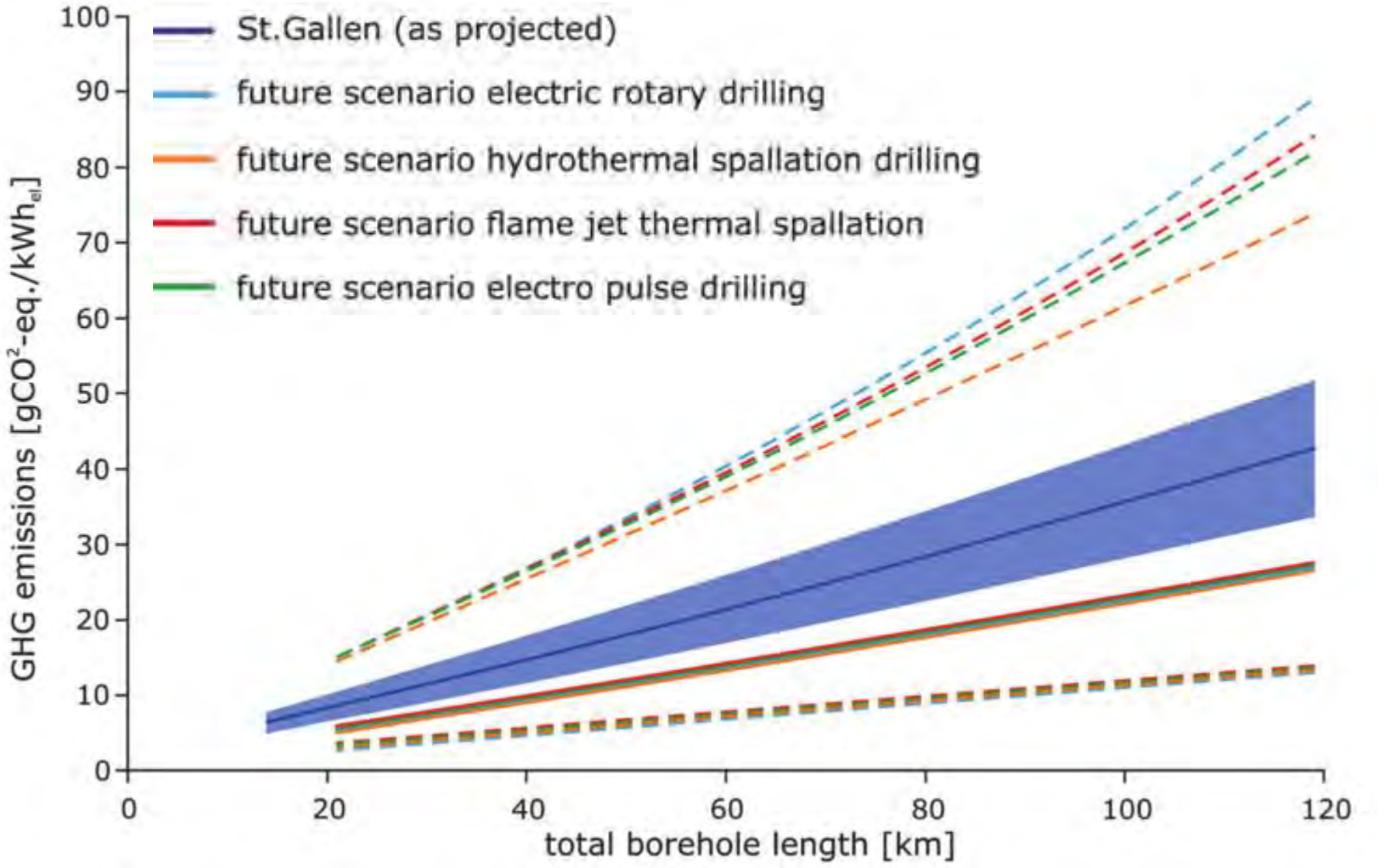


Impacts as function of total borehole

- **Review**: total borehole length **6-200km**

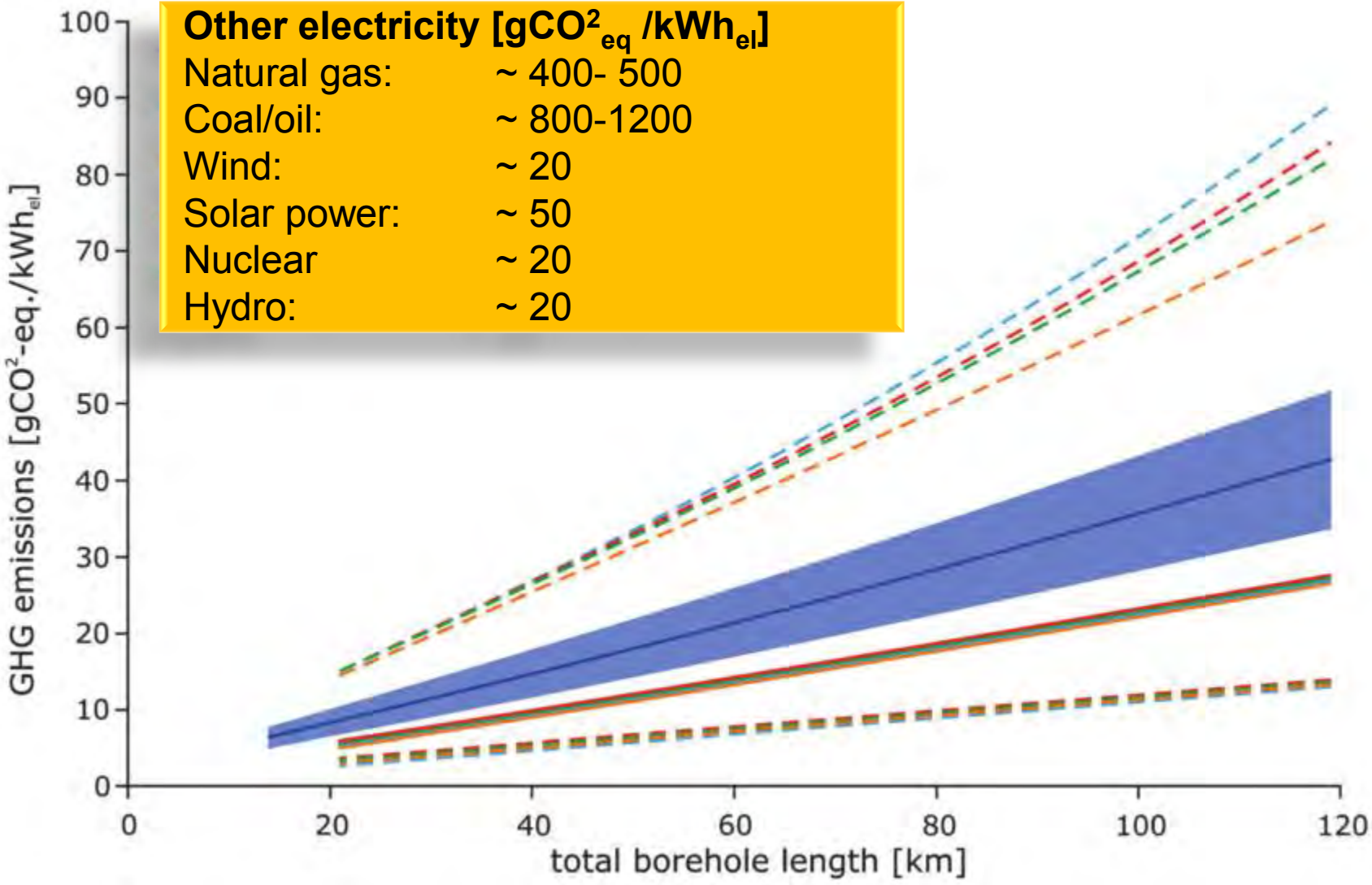


St.Gallen case



St.Gallen case

Other electricity [gCO^2_{eq} /kWh_{el}]	
Natural gas:	~ 400- 500
Coal/oil:	~ 800-1200
Wind:	~ 20
Solar power:	~ 50
Nuclear	~ 20
Hydro:	~ 20



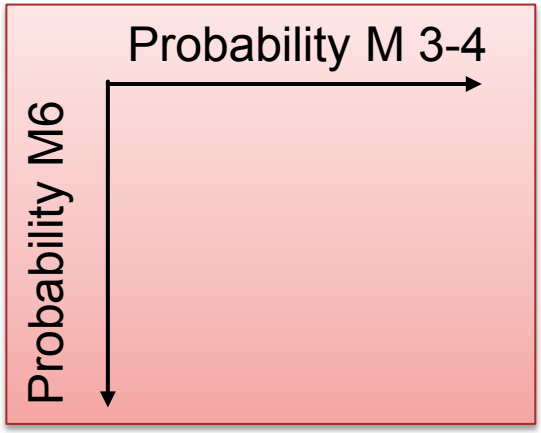
Seismic risks – missing LCIA

- Occurrence:
  - During drilling and operation phase (and exploration phase)
- Acceptance:
  - Limited as impacts occur locally not in other countries
- Effect
  - Observed earthquakes in Basel and St.Gallen no damage expected
    - In Basel lot of unjustified damages reported (previous events?) (Kraft et al. 2009: http://doi.org/10.1029/2009EO320001)
    - In St. Gallen no damages reported (mentality?)

Seismic risks in an LCA context

- Environmental impacts and impacts on man-made environment (damages to infrastructure)
  - Very high uncertainties make modeling difficult
  - Estimate damage in costs (earthquake studies)

- Generally many small and few large seismic events
  - Assume cumulated probabilities (30years)
    - M3-4: 100-1000%
    - M6: 1-2%



Cost estimates seismic events Basel

- 2 approaches resulted in ~130-140 million CHF impacts over 30 years
- Projected production of ~500 GWh:
  - **0.2 – 0.3 USD / kWh**

- Reasons
  - Relatively low electricity production (3 MW)
  - High population density
  - Conservative estimate

Recent study: Trutnevyte and Azevedo (2018)

- Expert assessments of costs and risks of seismic events >M3 and >M5
- Hypothetical plant rather high flow
  - 5.5 MW net (~1300 GWh/a)
- Total costs (30 years operation):
  - Geomean: 2.3 million USD
  - Arithmetic mean: 31 million USD
- **Cost / kWh**
  - **0.002 - 0.02 USD/kWh**

Environmental Research Letters

LETTER

Induced seismicity hazard and risk by enhanced geothermal systems: an expert elicitation approach

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Keywords: enhanced geothermal systems, induced seismicity, expert elicitation, risk assessment, risk governance

Supplementary material for this article is available online

Conclusion

- No scientific reason to abandon EGS exploration in Switzerland
  - Especially in light of Paris Agreement
  - Baseline when no sun

1815:
Tambora Eruption

Conclusion

- No scientific reason to abandon EGS exploration in Switzerland
  - Especially in light of Paris Agreement
  - Baseline when no sun
- Political issue ("Not In My Back Yard")
  - “Swissness”
    - clean local production, outsourced dirty supply chains
    - Federal, democratic system hinders developments
- More research needed

ETH zürich

Thank you for your attention!

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Impacts as function of total borehole (Menberg et al 2016)

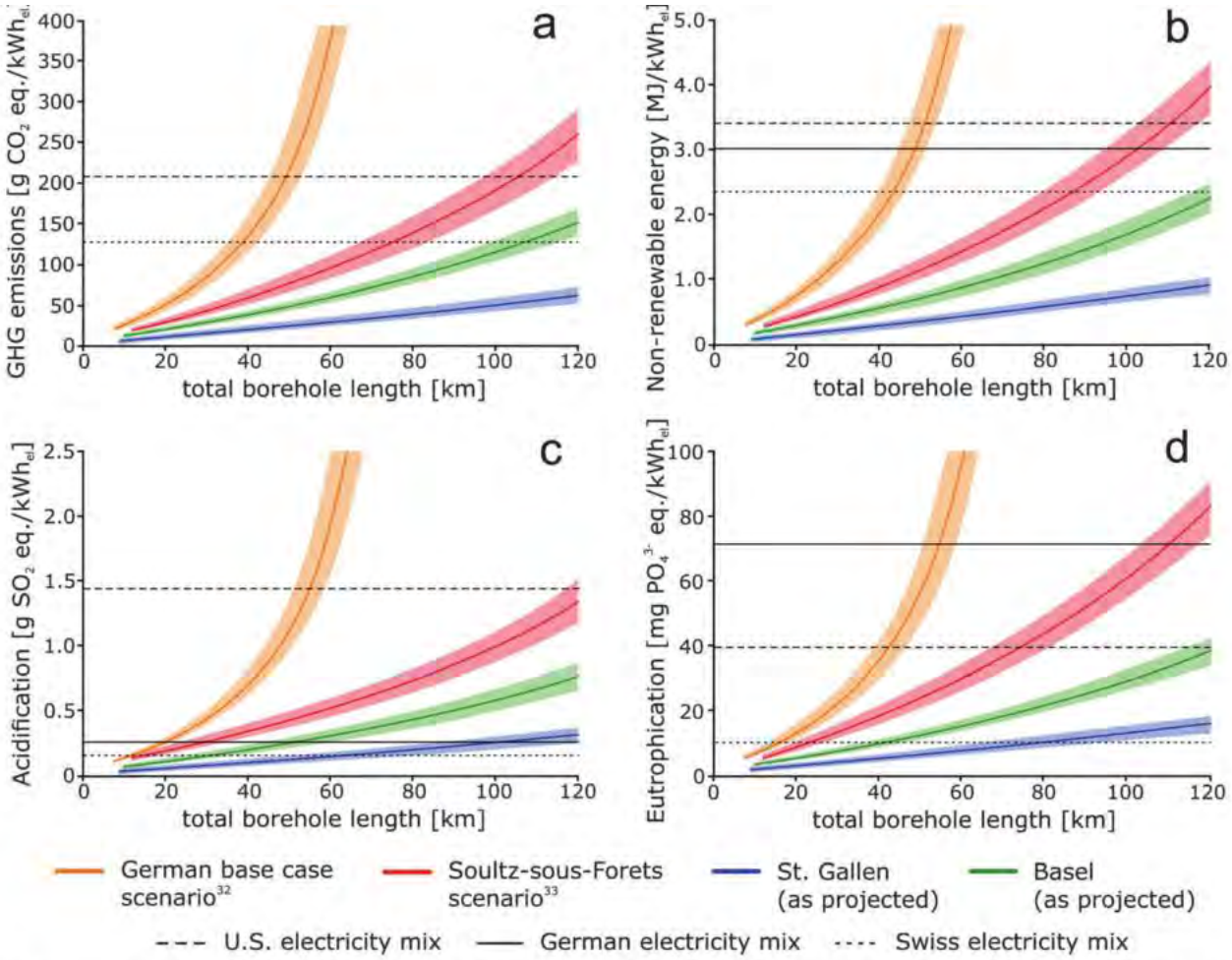
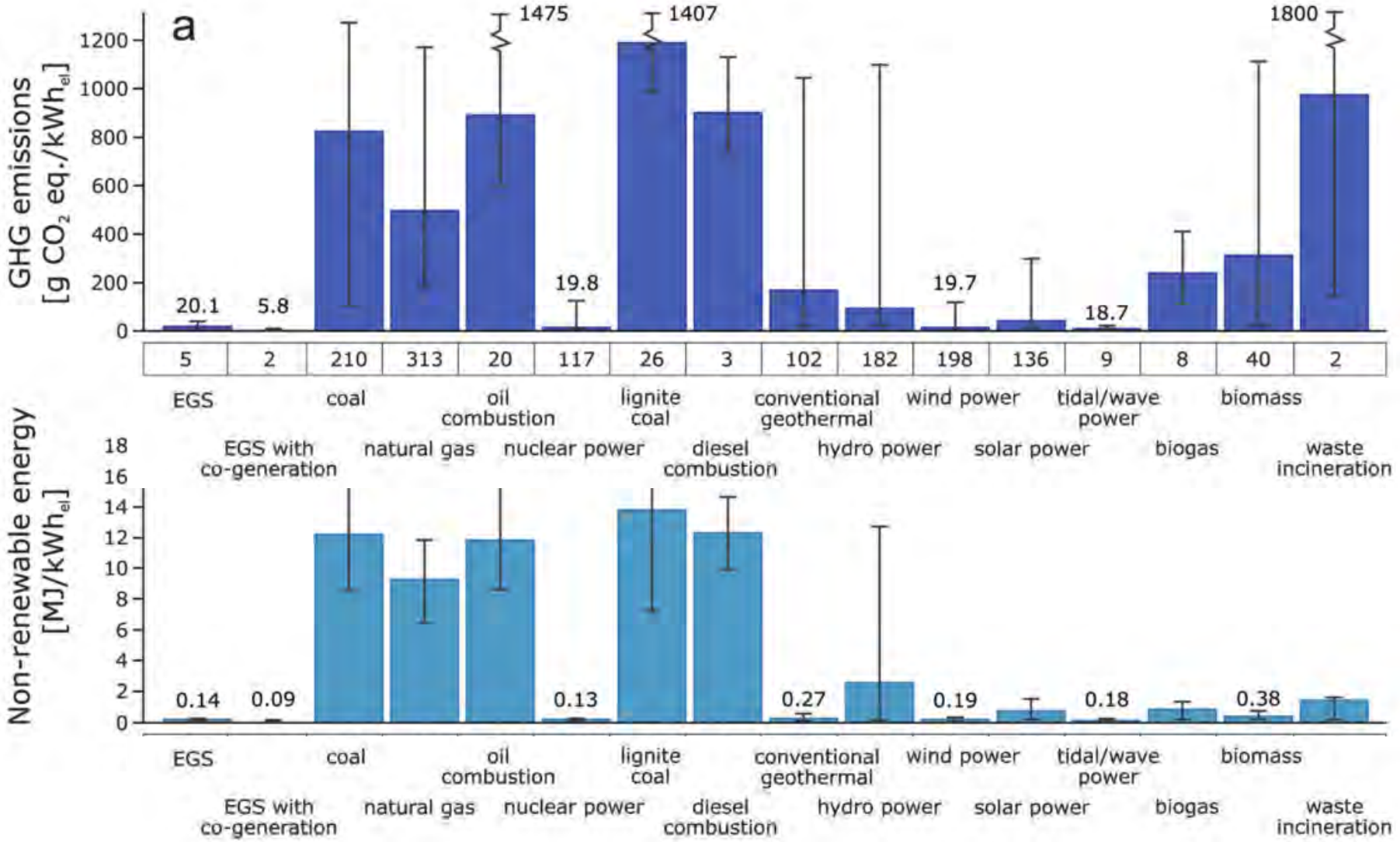


Fig. 4 (a) Life time GHG emissions, (b) non-renewable energy demand, (c) acidification and (d) eutrophication potential per produced kW h electricity for four EGS plants as a function of overall borehole depth (number of wells multiplied by the well depth). The German base case is identical to scenario A1 in Frick *et al.* and Soultz-sous-Forêts is identical to scenario case 6 in Lacirignola and Blanc.[32,33] Data for the emissions caused electricity mixes are taken from Ecoinvent 2.2.[59] The band accounts for the standard deviation of LCI uncertainty.

Comparison with other power
(Menberg et al 2016)



Caclulations impacts

Trutnevyte and Azevedo (2018):

Annual probability stimulation

- **M≥3 -> P 0.2%–95% during reservoir -> ~50% avg (geomean 5%)**
- **M ≥ 5 event span from 0.002%–2% -> ~ 1% avg (geomean 0.06%)**

Annual probability operation

- **M≥3 -> P 0.2%–100% during operation. -> ~50% avg (geomean 5%)**
- **M ≥ 5 event span from 0.003%–3% -> ~ 1.5% avg (geomean 0.1%)**

Costs

- **M3 cost 0.5 mio / event**
- **M5 cost 50 mio / event + 50 injuries and one fatality or none -> <50 DALYS**

Stimluation geomean:

= 5%* 0.5 mio = 0.03 mio
+ 0.06%*50mio = 0.03 mio

arithmean
=50%* 0.5 mio = 0.25mio
+1% * 50 mio= 0.5 mio

Operation geomean
= 30* 5%* 0.5 mio = 0.75 mio
+ 30* 0.1 %*50mio = 1.5 mio

Arithmean
= 30* 50%* 0.5 mio = 7.5 mio
+ 30* 1.5 %*50mio = 22.5 mio

Paper on expert judgements comes to a similar conclusion

Trutnevyte and Azevedo (2018) DOI 10.1088/1748-9326/aa9eb2

- "expert best-guess estimates of annualized exceedance **probabilities of an M≥3 event range from 0.2%–95% during reservoir stimulation and 0.2%–100% during operation. Best-guess annualized exceedance probabilities of M ≥ 5 event span from 0.002%–2% during stimulation and 0.003%–3% during operation. Assuming that tectonic M7 events could occur, some experts do not exclude induced (triggered) events of up to M7 too. If an induced M = 3 event happens at 5 km depth beneath a town with 10 000 inhabitants, most experts estimate a 50% probability that the loss is contained within 500 000 USD without any injuries or fatalities. In the case of an induced M = 5 event, there is 50% chance that the loss is below 50 million USD with the most-likely outcome of 50 injuries and one fatality or none**. As we observe a vast diversity in quantitative expert judgements and underlying mental models, we conclude with implications for induced seismicity risk governance."

Seismic risks in an LCA context

- Environmental impacts and impacts on man-made environment (damages to infrastructure)
  - Using data form Geology, there seems no to very low real impacts
  - Very high uncertainties make modeling difficult
  - Even with higher estimation impacts very low compared to other power production options
- Risks can be modeled and contain uncertainty as failure of dams in hydropower or climate risks (Kraft et al 2009)
  - No need to treat separately

Patrick Hädener BSc thesis:

Umweltbewertung eines Geothermie-kraftwerkes

~ Magnitude 3-4 ~ Magnitude 6	1 mal 4.44 Mio.	2 mal 8.88 Mio.	3 mal 13.33 Mio.	4 mal 17.77 Mio.	5 mal 22.22 Mio.	6 mal 26.66 Mio.	7 mal 31.11 Mio.	8 mal 35.55 Mio.	9 mal 40 Mio.
0.0100	91.391 Mio.	95.831 Mio.	100.28 1 Mio.	104.72 1 Mio.	109.17 1 Mio.	113.61 1 Mio.	118.06 1 Mio.	122.50 1 Mio.	126.95 1 Mio.
0.0111	100.95 6 Mio.	105.39 6Mio.	109.84 6Mio.	114.28 6 Mio.	118.73 6 Mio.	123.17 6 Mio.	127.62 6 Mio.	132.06 6 Mio	136.51 6 Mio.
0.0125	113.12 9 Mio.	117.56 9 Mio.	122.01 9 Mio.	126.45 9 Mio.	130.90 9 Mio.	135.34 9 Mio.	139.79 9 Mio.	144.23 9 Mio.	148.68 9 Mio.
0.0143	128.78 1 Mio.	133.22 1 Mio.	137.67 1 Mio.	142.11 1 Mio.	146.56 1 Mio.	151.00 1 Mio.	155.45 1 Mio.	159.89 1 Mio.	164.34 1 Mio.
0.0166	148.78 0 Mio.	153.22 0 Mio.	157.67 0 Mio.	162.11 0 Mio.	166.56 0 Mio.	171.00 0 Mio.	175.45 0 Mio.	179.89 0 Mio.	184.34 0 Mio.
0.0200	178.34 3 Mio.	182.78 3 Mio.	175.23 3 Mio.	191.67 3 Mio.	196.12 3 Mio.	200.56 3 Mio.	205.01 3 Mio.	209.45 3 Mio.	213.90 3 Mio.