Task 4.2

Task Title

Global observatory of electricity resources

Research Partners

Technology Assessment Group, Energy Economics Group at Paul Scherrer Institute (PSI), Institute of Geophysics (IfG) at ETH Zurich

Current Projects (presented on the following pages)

At the annual conference 2015, five posters were presented for Task 4.2, which can be assigned to three topical areas:

Energy Perspectives Extension & Update

Perspectives for Swiss electricity supply: Potentials, costs and environmental assessment
S. Hirschberg, C. Bauer, Y. Bäuerle, S. Biollaz, P. Burgherr, B. Cox, T. Heck, M. Lehnert, A. Meier, M. Saar, W. Schenler, M.Q. Tran, K. Treyer, F. Vogel, C. Wieckert, X. Zhang, M. Zimmermann

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Future deep geothermal plants in Switzerland: Capacity, cost and environmental impacts
K. Treyer, W. Schenler, P. Burgherr, S. Hirschberg

Hydropower in Switzerland: Potentials, costs and environmental assessment
C. Bauer, M. Lehnert

Scenario Modeling

Exact dispatch solutions of stochastic hydropower problems
M. Densing, T. Kober

Comparative Risk Assessment

Comparative assessment of hydrogen accidents risk
M. Spada, P.B. Rouelle, P. Burgherr, D. Giardini

Task Objectives

The Global Observatory provides a comprehensive analytical framework for technology characterization and trend identification that can be applied in a consistent manner across a broad portfolio of current and future technologies. In addition to geo-energies and hydropower, a broad set of technologies are considered, including new renewables (e.g. solar photovoltaic, solar-thermal, wind onshore and offshore, biomass, geothermal, wave and tidal), fossil energy carriers (with and without CCS), nuclear energy and consideration of co-generation. Its two main objectives are the following:

- Characterization and sustainability assessment of current and future technologies
- Evaluation of existing trends, projections, and scenarios

Interaction Between the Partners – Synthesis

The Global Observatory has established links with the various work packages within the SCCCEr-SoE to make use of the available expertise in this SCCER. In addition, there are collaborations with several other SCCERs, namely Biosweet (for biomass), Storage, Mobility and Furies. Finally, the involvement of PSI's Laboratory for Energy Systems Analysis in many different projects ensures that results relevant for the Global Observatory can be easily incorporated.

Highlights 2016

- The Global Observatory focuses on Switzerland, but also considers European and global scales.
- Detailed technology characterization forms the basis for a holistic sustainability assessment of electricity generation options.
- The "Energy Perspectives Update and Extension" project jointly funded by SFOE, SCCER SoE and Biosweet provides a consistent evaluation of electricity generation technologies potentially relevant for Swiss supply until 2050, addressing potentials, costs, and environmental aspects.
- Swiss TIMES Energy system Model (STEM), a whole energy systems model of Switzerland, is extended with a detailed hydro module. This hydro module includes hydro power plants disaggregated by river basins and reservoirs; and their historical availability.
- A stochastic hydro dispatch algorithm has been developed to generate insights on influence of water level and spot market electricity price on profitability of hydro power plants.
- In collaboration with Task 4.1 and support of PSI's risk team within the Future Resilient Systems (FRS) project of the Singapore-ETH Centre (SEC), a new, interactive, GIS-based version of PSI's Energy-Related Severe Accident Database (ENSAD) was developed for hydropower, and accidents in other energy chains will be gradually added.
- A comparative risk assessment for H2 accidents was carried out, and the results were compared to other technologies (fossil, hydro, new renewables).

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Perspectives for Swiss electricity supply: Potentials, costs and environmental assessment

PAUL SCHERRER INSTITUT

Stefan Hirschberg, Christian Bauer, Yvonne Bäuerle, Serge Biollaz, Peter Burgherr, Brian Cox, Thomas Heck, Maxim Lehnert, Anton Meier, Martin Saar, Warren Schenler, Minh Quang Tran, Karin Treyer, Fredi Vogel, Christian Wieckert, Xiaojin Zhang, Martin Zimmermann (PSI, ETHZ, EPFL)

Motivation & objectives

Electricity generation technologies, potentially relevant for Swiss supply until 2050, are evaluated concerning their technical potentials, costs, and their environmental impacts.

This technology assessment is carried out as a common project of the Swiss Federal Office of Energy (SFOE) and SCCER SoE with additional contributions by SCCER Biosweet. The results will serve as technological input to the forthcoming update of the "Energie-perspektiven 2050" as well as part of SFOE's technology monitoring.

Main contributors are researchers at the Laboratory for Energy System Analysis (LEA) at PSI. In addition, PSI's Energy and Environment Research Division, ETHZ and EPFL are participating in these activities.

Technology overview

Renewable, fossil, and nuclear technologies are evaluated. Generation can take place within Switzerland or abroad with subsequent import of electricity.

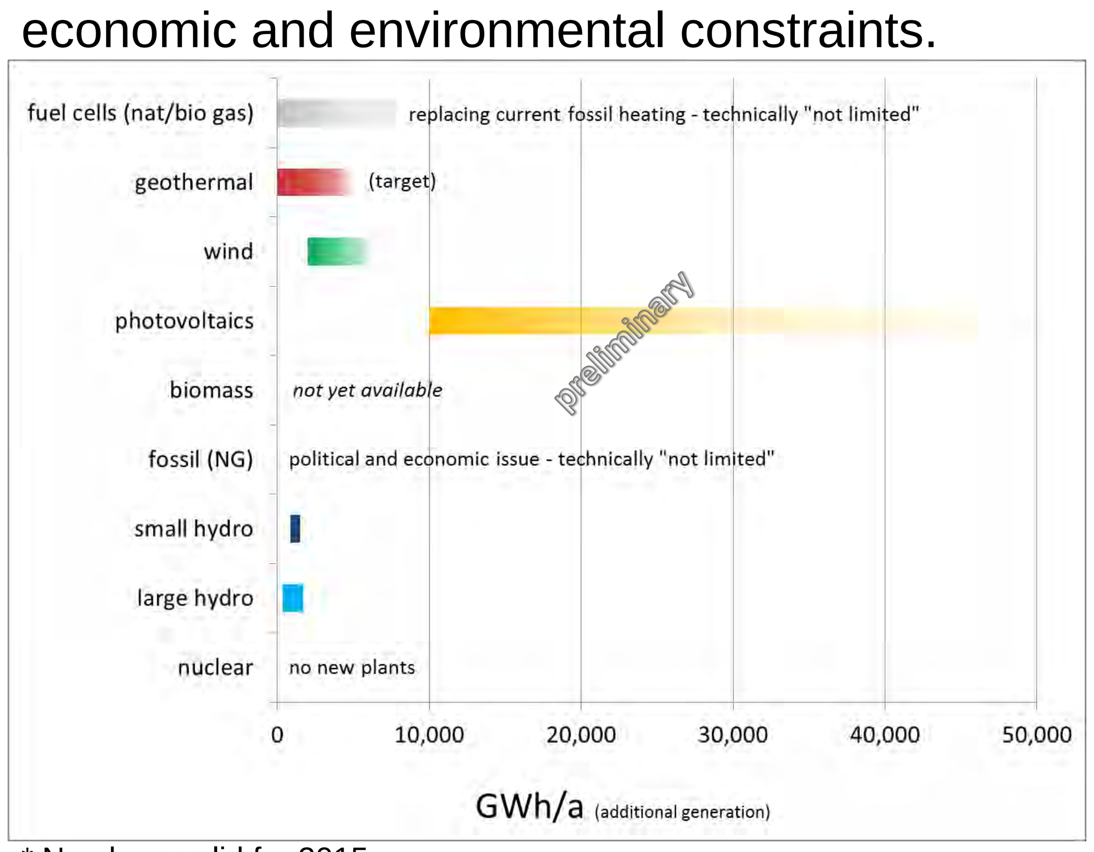
The assessment takes into account expected future technology development until 2050.

Electricity generation potential

Current* electricity generation in Switzerland is dominated by hydro (60%) and nuclear (34%) power. Photovoltaic panels, biomass, and fossil fuels each contribute about 2% to the production mix.

In terms of additional generation until 2050, solar photovoltaics exhibits the highest technical potential, if the majority of roof-tops can be covered with panels. The potential of deep geothermal power is most uncertain.

Technical potentials do not provide a perspective on public acceptance, economic and environmental constraints.



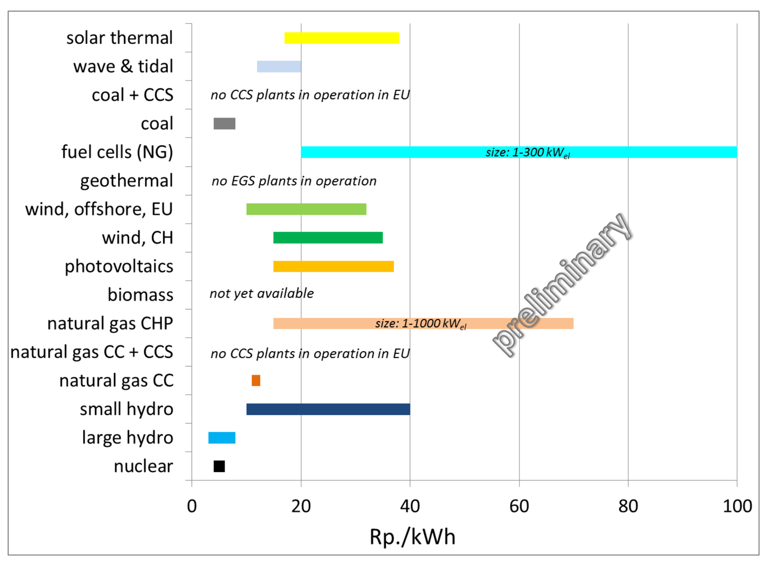
Technical potentials are not quantified for certain technologies, for which this term is meaning-less, i.e. natural gas power plants and electricity imports.

* Numbers valid for 2015.

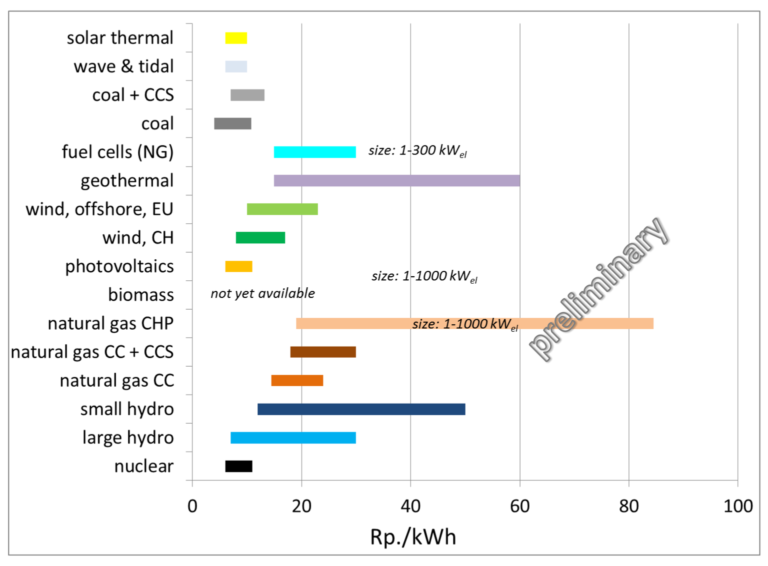
Electricity generation costs

Generation cost estimates are provided for today (left) and 2050 (right).

2015



2050



Costs of currently immature technologies – deep geothermal, solar thermal, wave power, CCS – are associated with highest uncertainties.

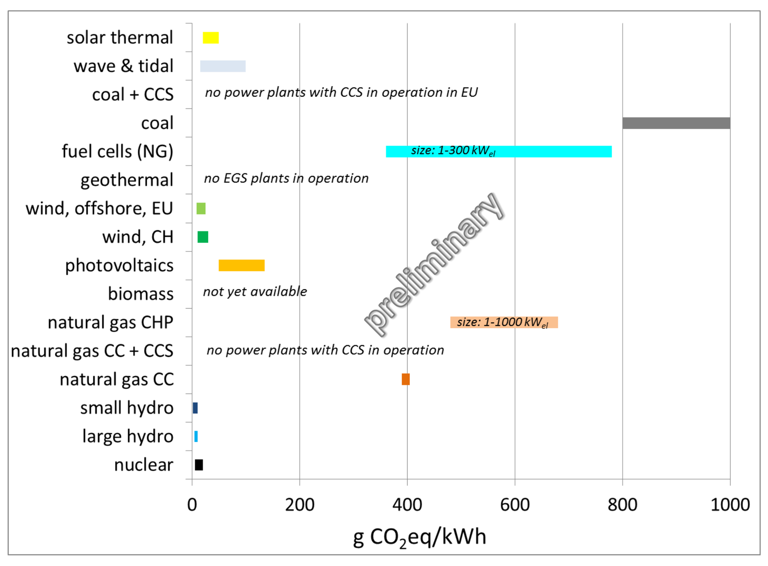
Cost ranges reflect both uncertainties as well as variability in technology performance, site conditions, technology characteristics and future technology development.

While costs of established technologies – hydro, nuclear and natural gas power plants – will remain stable or tend to increase in the future, costs of renewables are expected to drop substantially until 2050. However, these cost estimates do not consider any system costs related to electricity grid issues, potentially necessary backup power and storage capacities, etc.

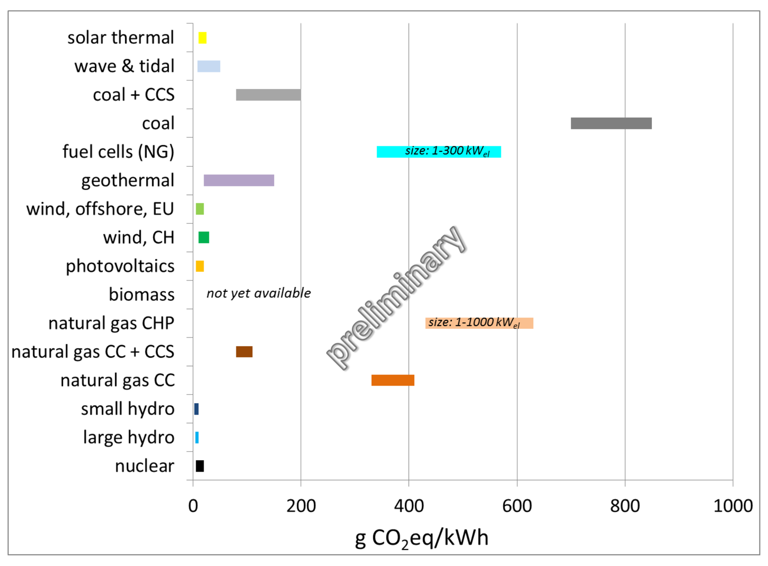
Environmental burdens: Greenhouse Gas (GHG) emissions

Environmental burdens are quantified based on Life Cycle Assessment (LCA), taking into account construction, operation, and end-of-life of power plants with all associated material supply chains and emissions into the environment. The graphs below show – as the key indicator for environmental performance – life-cycle GHG emissions (GWP 100a, IPCC 2007) representing impacts on climate change of current technologies (left) and the estimated figures for 2050 (right), according to own calculations and (ecoinvent 2015).

2015



2050



Emission ranges reflect both uncertainties as well as variability in technology performance, site conditions, technology characteristics and future technology development.

Currently, hydro, nuclear and wind power cause the lowest GHG emissions. Future technology development is expected to reduce emissions from photovoltaics, solar thermal, wave and tidal power to similar levels. Geothermal power shows a broad range, reflecting large uncertainties and dependency on local conditions. Natural gas power plants with carbon capture and storage (CCS) could contribute to a "climate-friendly" electricity mix in the future.

In addition to GHG emissions, further indicators for potential impacts on human health and ecosystems are quantified (see poster "Hydropower in Switzerland: Potentials, costs and environmental assessment").

References

Hirschberg S., et al. (2016) "Potentials, costs and environmental assessment of electricity generation technologies." *To be published.* Paul Scherrer Institut.

ecoinvent (2015) "The ecoinvent LCA database, v3.2, «allocation, cut-off by classification»." The ecoinvent center.

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Future deep geothermal plants in Switzerland: Capacity, cost and environmental impacts

Karin Treyer, Warren Schenler, Peter Burgherr, Stefan Hirschberg
Technology Assessment Group, Laboratory for Energy Systems Analysis, Paul Scherrer Institut (PSI)

1) Motivation

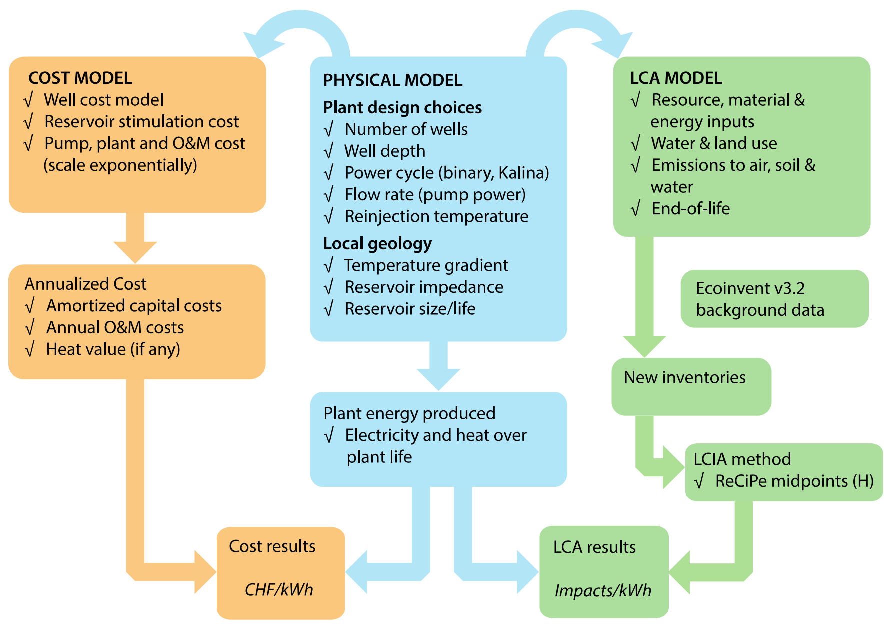
- **70 TWh of electricity** have been produced globally in 2015 from deep geothermal plants (DGP) – none of them in Switzerland (CH).
- The International Energy Agency (IEA 2011) estimates **potential generation in 2050** from DGP of **1400 TWh/**year plus 5.8 EJ/year of heat.
- The most available growth is projected to be in Enhanced Geothermal Systems (**EGS)** plants, as hydrothermal potential is limited. The Swiss energy strategy foresees a **contribution of 4-5 TWh** from DGP by 2050 to the Swiss electricity supply.
- No economically operational EGS plants yet exist worldwide.
- Our goal is to recognize and understand the **interplay between key factors for future EGS** plants in Switzerland as part of a comprehensive project (Hirschberg et al. 2016) assessing the future perspectives of the overall Swiss electricity supply on behalf of the Swiss Federal Office of Energy and the SCCER SoE.
- We have evaluated these interlinked topics by a new model, see 2).

3) Cases

1) From Hirschberg et al. (2015): **3 triplet cases** show the range of possible results (2.9 MW – 14.6 MW; 68-20 Rp./kWh, 42-6 gCO_2eq/kWh).
2) Update: **3 doublet cases (a) and 3 triplet cases (b)** show a range of plants which could potentially be built in Switzerland:

	Poor	Medium	Good
General conditions / well cost	Not as expected / high	Average / medium	Above average or expectations / low
Gradient [°C/km]	30	30	35
Reservoir impedance [MPa per L/s]	0.25	0.2	0.15
Flow rate per well [L/s]	40	50	75 (a,optimum)/50 (b)
Well cost [MCHF/5km well]	30	24	18
LCOE [Rp./kWh]	(a) 58 / (b) 45	(a) 41 / (b) 33	(a) 18 / (b) 16
g CO_2eq/kWh	(a) 84 / (b) 61	(a) 67 / (b) 51	(a) 30 / (b) 27

2) The PSI model: an underlying physical model coupled to both cost and Life Cycle Assessment (LCA) models.



Physical inputs determined by plant design:
- **Wells**: Location, number, depth, diameter
- **Stimulation**: Duration, pressure, volume
- **Operation**: Flow rate, input temperature, power cycle

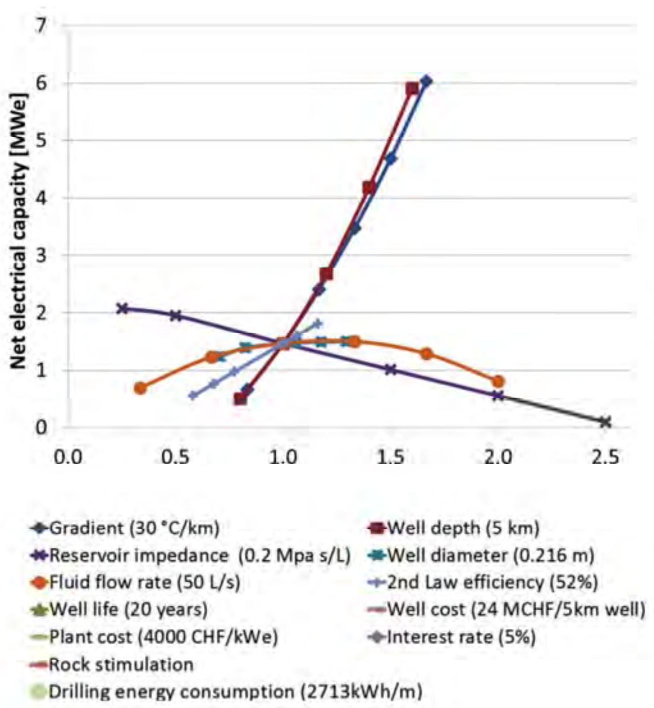
Physical results subject to uncertainty:
- Gradient (drives fluid temperature and thermal efficiency)
- Success of stimulation (low Impedance reduces pump losses, big reservoir size increases well life)
- Brine chemistry (affects well and plant O&M, and return temperature)

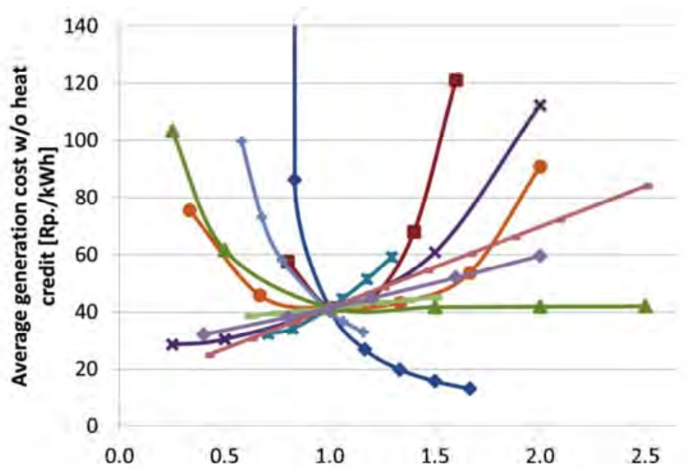
Other important uncertainties:
- Well cost (experience is mainly based on oil and gas wells that are typically in different geology and to shallower depths than for EGS)
- Energy use for drilling

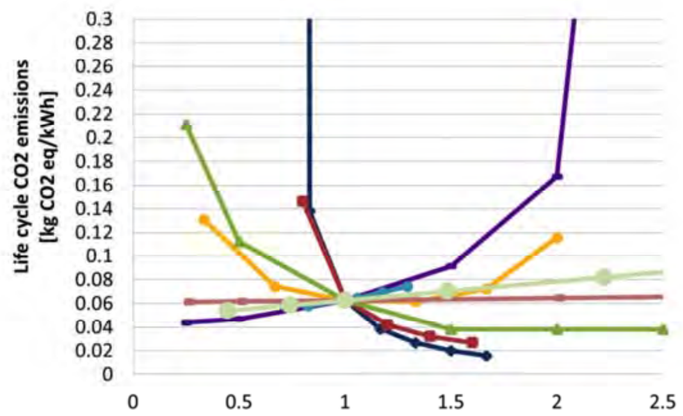
Parameter combinations have been set up to show CH cases, see 3).

4) Sensitivities of net capacity, average generation cost/kWh and CO_2 equivalent emissions/kWh - Highlights

- The *steeper the line*, the more sensitive a result is. Values can quickly go towards very high or low values.
- The higher the *gradient* the better. 30°C/km is the Swiss (& global) average.
- *Well costs and energy use* both increase exponentially with depth, and are decisive for LCOE & environmental impact results.
- *Deeper wells* give a higher capacity BUT also higher costs & env. impacts due to exponential increases in cost, materials and energy use for deeper wells.
- Lower *well diameter* gives higher pump losses and lower net capacity.
- *Higher impedance* leads to lower net capacity. May be decreased by stimulation (but outcome is uncertain).
- The *flow rate* shows an optimum at about 75 L/s. Lower flows reduce heat production, while higher flows increase pumping losses enough to reduce net generation.







X-axis for all graphs: Sensitivity factor equals ratio to base value given in brackets above

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Discussion

- LCOE, use of materials and energy, and environmental impacts of potential future EGS plants depend significantly upon net capacity.
- LCOE may decrease to zero or even to negative cost - if the excess heat can be sold. Well cost dominates the LCOE, while energy & materials used for well drilling dominate the environmental impacts. Low reservoir impedance (via stimulation) and a high gradient are important for all results.
- With experience in exploration, drilling and stimulation, the LCOE may be reduced to about 13 Rp./kWh in future (without heat sales).
- Environmental impacts are low if drilling is done with an electricity mix that has a low or zero share of fossil fuels.
- If technical challenges can be overcome, electricity from EGS can provide an important contribution to the future power supply in Switzerland.

This work is an update of our research presented in Hirschberg, S., S. Wiemer, P. Burgherr (eds.). 2015. "Energy from the Earth. Deep Geothermal as a Resource for the Future?" *Centre for Technology Assessment TA Swiss. vdf Hochschulverlag AG, ETH Zuerich. ISBN 978-3-7281-3654-1. Download: ISBN 978-3-7281-3655-8 / DOI 10.3218/3655-8.* See Hirschberg S., et al. (2016) "Potentials, costs and environmental assessment of electricity generation technologies." *To be published.* PSI.
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Hydropower in Switzerland: Potentials, costs and environmental assessment

PAUL SCHERRER INSTITUT

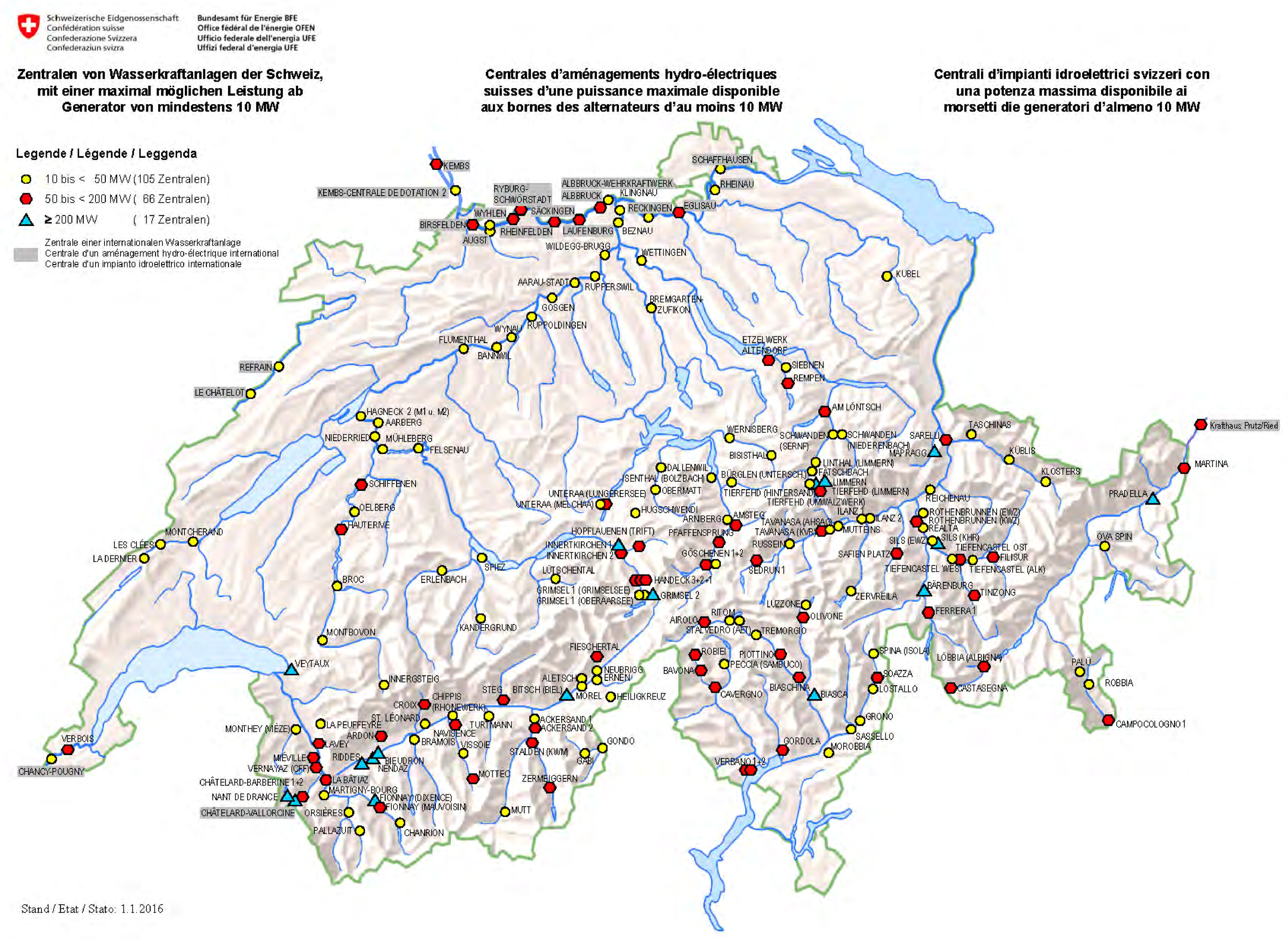
Christian Bauer, Maxim Lehnert (Paul Scherrer Institut)

Motivation & objectives

Hydropower is the most important source of electricity in Switzerland with a central role in the Swiss energy strategy 2050. The perspectives of hydropower in Switzerland are evaluated as part of a comprehensive project (Hirschberg et al. 2016) assessing the future perspectives of the overall Swiss electricity supply on behalf of the Swiss Federal Office of Energy and the SCCERs SoE and biosweet.

The evaluation includes an estimation of future hydropower generation **potentials**, electricity generation **costs**, and the assessment of **environmental aspects**. Both large (>10 MW_{el}) (LHP) and small (<10 MW_{el}) hydropower plant (SHP) categories are considered.

Current status of hydropower in Switzerland



Large hydropower

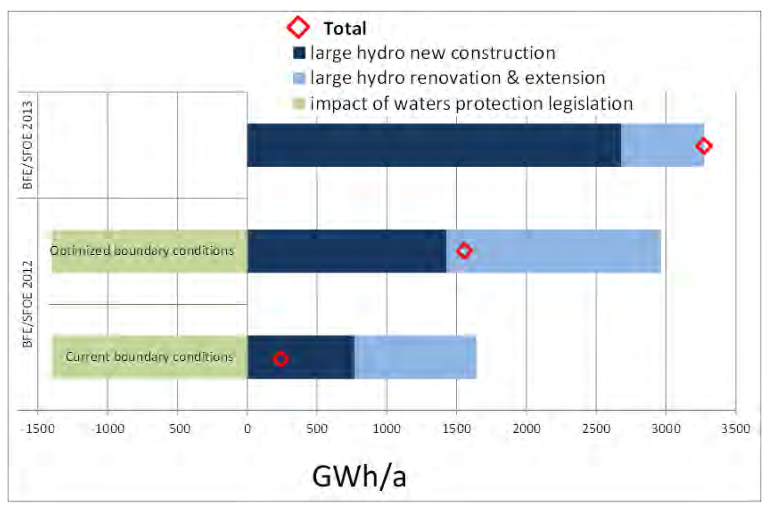
Power plant type		Installed capacity [MW]	Expected annual production [GWh]	Expected winter production [GWh]	Expected summer production [GWh]
Run-of river	Lauf-wasser	3941	17’312	6173	11’139
Storage	Speicher	7966	17’295	8083	9212
Pumped storage[1]	Pump-speicher	1384	1568	936	631
Pumped storage[2]	Umwälz	469	0	0	0
Total[3]		13’760	36’175	15’192	20’982

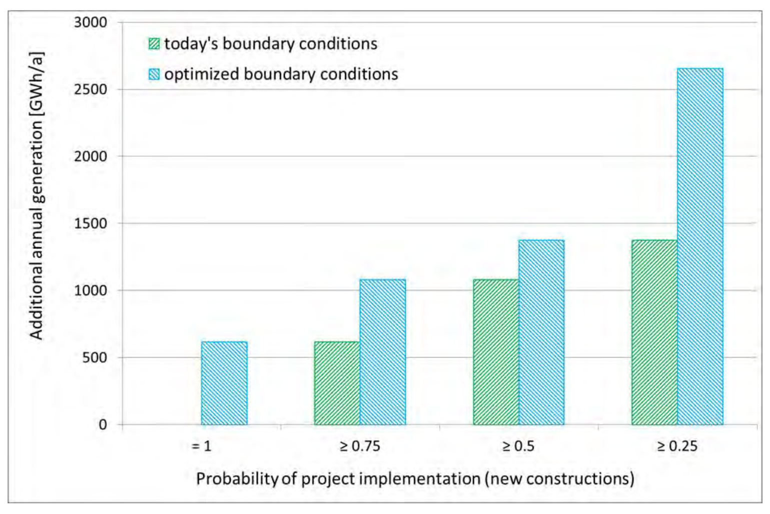
Small hydropower

Plant category	Number of plants [-]	Installed capacity [MW]	Expected annual production [GWh/a]	Share in total Swiss hydropower production
1-10 MW	204	714	2’728	7.1%
0.3-1 MW	226	131	605	1.6%
<0.3 MW	700	41	190	0.5%

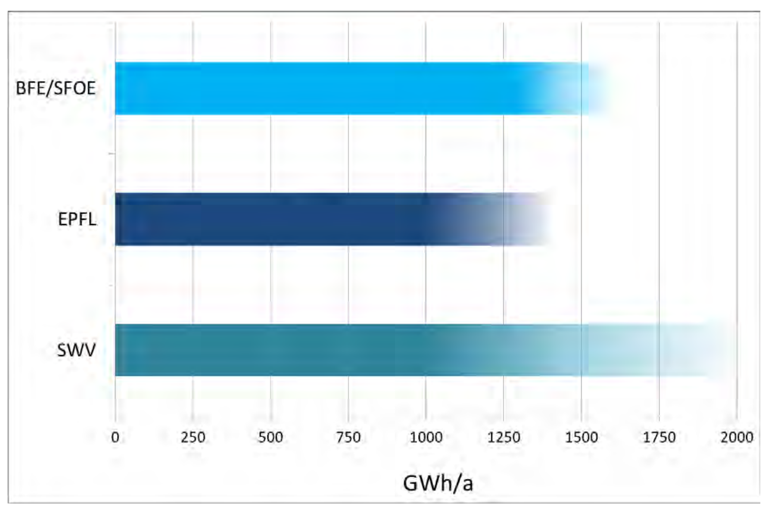
Future electricity generation potential of hydropower

Large hydropower





Small hydropower

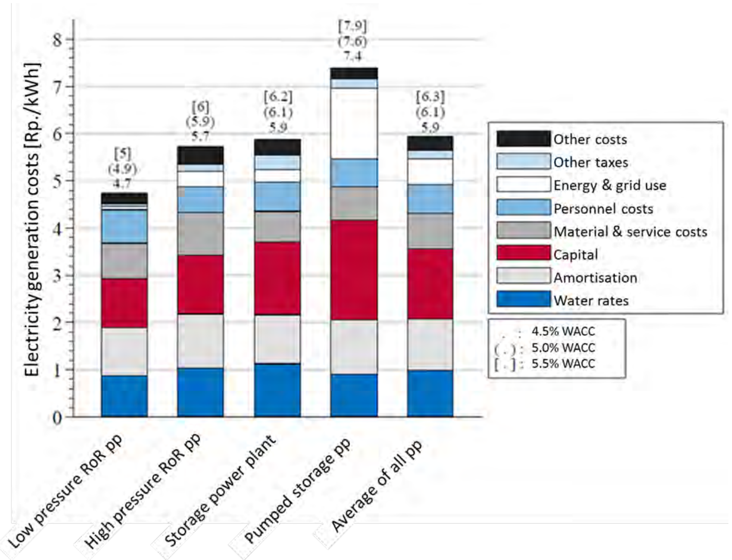


- The overall additional generation potential of hydropower in Switzerland is in the range of 1.2-3.5 TWh/a, considering new plants and renovation/extension
- Slightly incresing the height of ~20 existing dams could provide further 2 TWh/a, mainly in winter.

Electricity generation costs

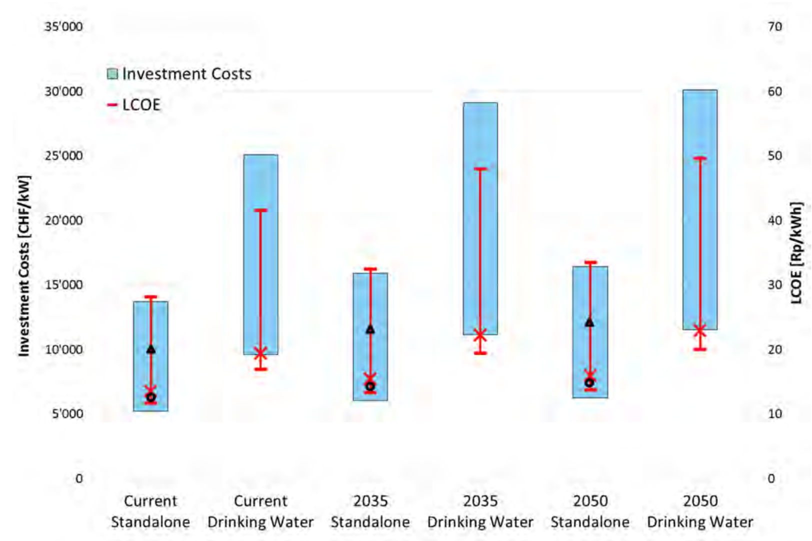
Large hydropower

Current generation costs

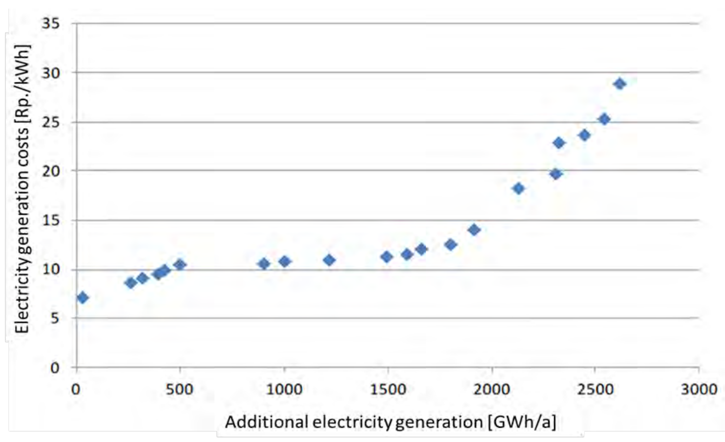


Small hydropower

Current & future generation costs



Future generation costs

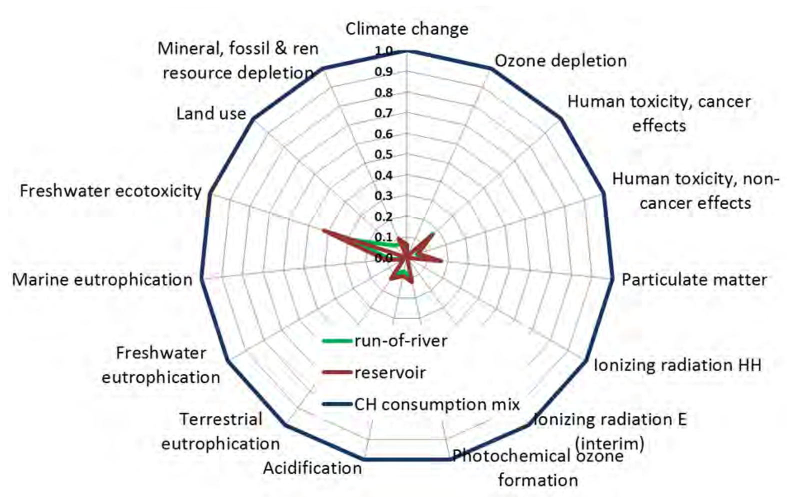


- Generation costs of current LHP plants are in the order of 5-8 Rp. per kWh, while SHP plant generation costs are in the order of 10-40 Rp./kWh.
- Future costs are very site specific – about 2 TWh/a (LHP) can be generated for 7-15 Rp./kWh.
- Future SHP costs are expected to increase slightly.

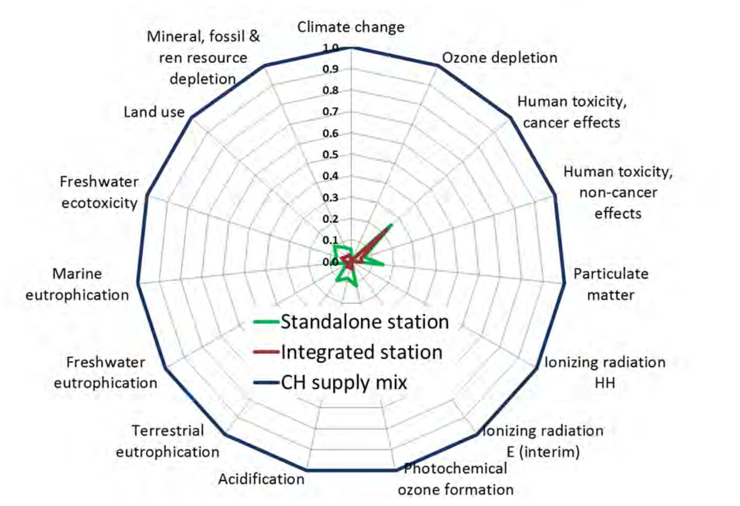
Environmental burdens

Environmental burdens are quantified based on Life Cycle Assessment (LCA), taking into account construction, operation, and end-of-life of power plants with all associated material supply chains and emissions into the environment. The graphs below show the potential environmental impacts of LHP (left) and SHP (right), according to (Hauschild et al. 2013), compared to the Swiss electricity mix (ecoinvent 2015). The impacts are normalized to the ones of the consumption mix (=1) for each indicator. Compared to the Swiss mix, the environmental performance of LHP and SHP is excellent.

Large hydropower



Small hydropower



However, site-specific, small scale impacts on ecosystems are not taken into account by the LCA methodology and have to be evaluated for each power plant individually (Weber & Schmid 2014).

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Exact dispatch solutions of stochastic hydropower problems

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Motivation: New approach for dispatch optimization

Traditional approach to hydropower dispatch optimization:

- Improve models by introducing more details (technical, etc.)
- Then: Solve the (large-scale) optimization problem numerically

→ Numerical solutions may be accurate, but lack analytical insight

Alternative approach for simple dispatch problems:

- Closed-form solutions
- Hence: Decision-makers get analytical insight on influence of water-level, spot-price, pump/turbine-capacity
- Some details must be neglected; but: Stochastic prices (in the simplified form of "averages"), and arbitrarily (!) many time-steps can be modelled

Scope of research:

- Optimal operation of energy storage and of flexible generation are central operational conditions for Energy Strategy 2050
- General understanding of optimal dispatch of stored energy against exogenous random energy prices (electricity is example)

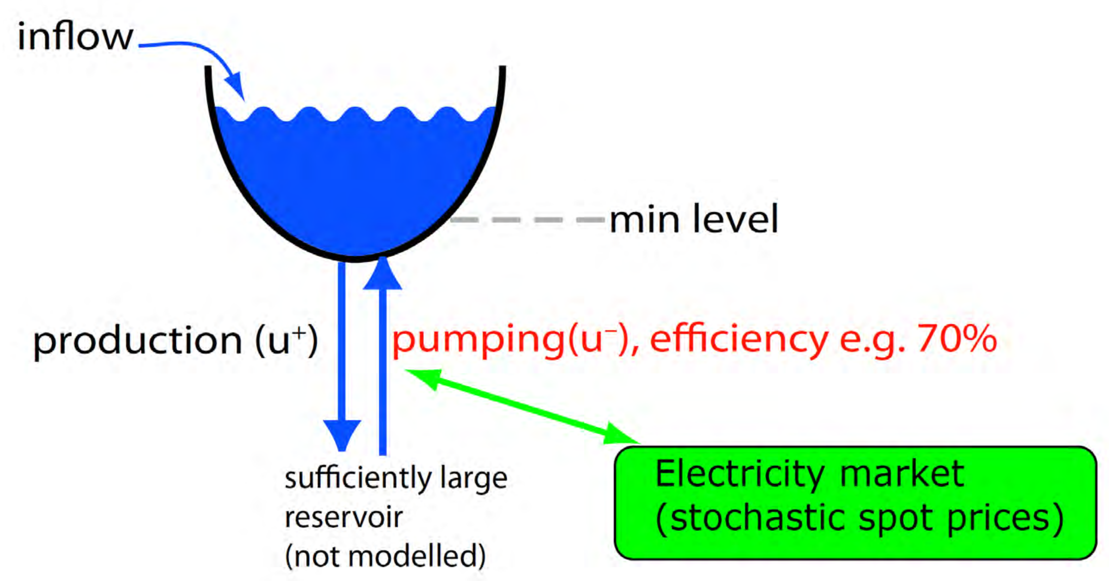
Status of research:

- Results available for: (i) Several pumped-storage reservoirs with multiple time-steps, (ii) ancillary services

Single-period hydropower pumped-storage dispatch

Model simplifications:

- Single-period model (steady-state model)
- Inflow is modelled in expectation (i.e. as an average over price scenarios). The average is added to the usable water level.
- Constraint on usable water level has to hold only in expectation
- No minimal turbine/pump constraint (reality: 10-40% capacity)



Objective function: Maximize expected profit of

production of electricity, priced at spot price *S*,
+ **pumping** water (i.e., electricity) with efficiency c (e.g. 75%):

$$\max_{u^\pm} \mathbb{E}\left[Su^+(S) - \frac{1}{c}Su^-(S)\right]$$

$$\text{s.t.} \begin{cases} l_0 - \mathbb{E}\left[u^+(S) - u^-(S)\right] \geq l_{\min} \\ 0 \leq u^\pm(S) \leq u^\pm_{\max} \end{cases}$$

S:	Spot electricity price, random variable (EUR/MWh)
$u^{+/-}(S)$:	Dispatch (turbine/pumping) (MWh) as function of *S*
l_0:	Expected usable water (water level + inflow) (MWh)
$u_{max}^{+/-}$:	Turbine/pumping-capacity (MW)
E[.]:	Expectation (= average over all electricity price scenarios)

Conclusion (pumped-storage):

Optimal dispatch is of bang-bang-type, i.e.,

- Produce at maximal capacity whenever electricity price $S \geq q$,
- Pump at maximal capacity whenever $S \leq cq$, where q is marginal value of constraint on water level

Single-period hydropower storage dispatch with option for ancillary service

Model simplifications:

- Single-period model (steady-state model)
- Inflow is modelled in expectation (i.e. as an average over price scenarios). The average is added to the usable water level.
- Constraint on usable water level holds only in expectation
- Simplified reimbursement of ancillary service as an aggregated total of capacity payment and historic average of energy payment
- No minimal technical turbine limits

Objective function: Maximize expected profit of

production of electricity, priced at spot price *S*,
+ **ancillary service** (fixed production level + capacity payment)

$$\left.\begin{array}{r} \max\limits_{u(\cdot),u_a} \mathbb{E}\left[S(u(S)+u_a)\right] + p_a u_a \quad \text{s.t.} \\ \mathbb{E}[u(S) - u_a] \geq l, \\ u(S) + 2u_a \leq u^+_{\max}, \\ u(S), u_a \geq 0, \end{array}\right\}$$

S:	Spot electricity price, random variable (EUR/MW)
u(S):	Free dispatch as function of electricity price *S*
u_a:	Set-point of ancillary service, agreed with TSO (MW)
p_a:	Total payments for providing ancillary service (EUR/MW)
l:	Usable water (= water level + inflow in expectation) (MWh)
u_{max}^+:	Turbine capacity (MW)
E[.]:	Expectation (= average over all electricity price scenarios)

Optimal solution (formula, main feature further below):

$$\left.\begin{array}{l} \hat{U} = \hat{u}(S) = \left(u^+_{\max} - 2\hat{u}_a\right)1_{\{S\geq\hat{q}\}} \\ \hat{u}_a = \left(\frac{1}{2}u^+_{\max} - \frac{l - \frac{1}{2}u^+_{\max}}{1 - 2\mathbb{P}[S \leq \hat{q}]}\right)1_{\{p_a > \mathbb{E}[|S-m|]\}} \end{array}\right\}$$

1_{S>q}:	Indicator function: If spot price S is higher or equal than q, then 1, else 0. Hence, if 1, then free production is possible.
q:	Marginal value of the water constraint
m:	Median of electricity spot price distribution
E[|S-m|]:	Mean absolute deviation of spot price distribution
P[S ≤ q]:	Probability that spot price *S* is lower or equal *q*

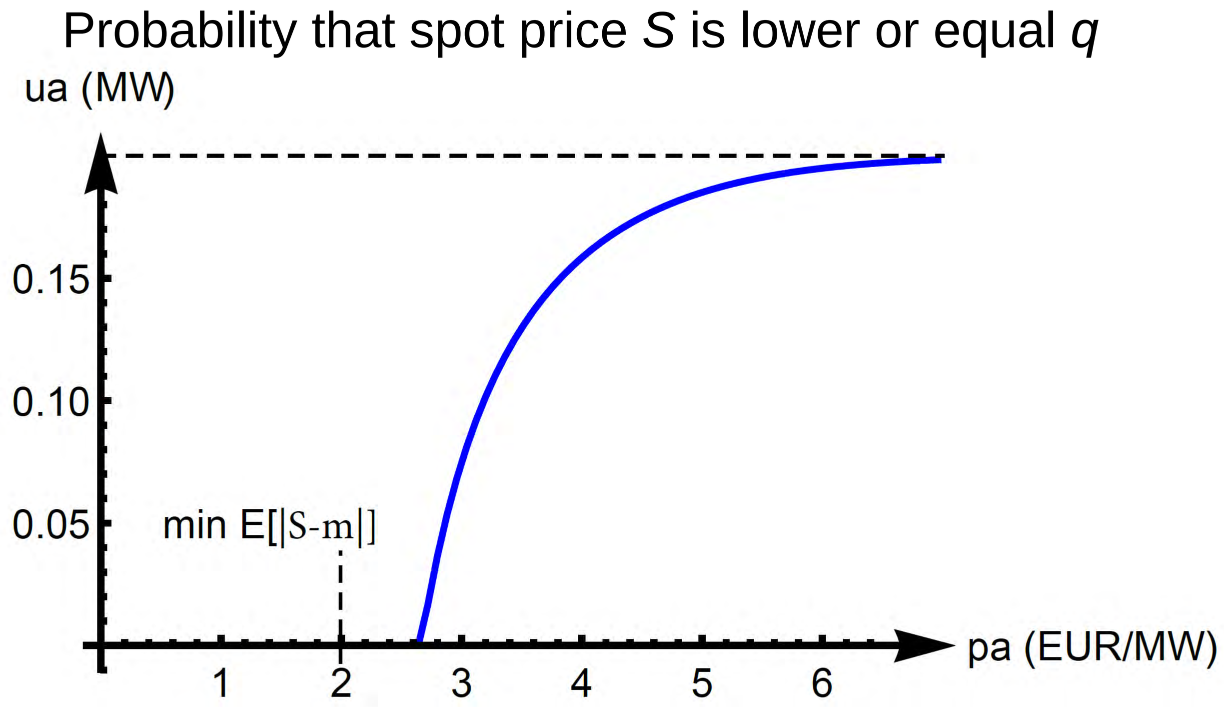


Figure 3: Ancillary service u_a as a function of the reimbursement p_a. Parameters: $u^+_{\max} = 1$; $l = 0.8$; random variable $S \sim N(10, \sigma = 2.5)$

Conclusion (ancillary service):

Sine-qua-non condition to enter ancillary service: Total expected payment of ancillary service must be higher than mean absolute deviation of spot price (volatility of spot price)

References

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Comparative assessment of hydrogen accidents risk

In cooperation with the CTI

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Introduction

Within SCCER SoE this work is part of PSI's contribution to Task 4.2 on "Global Observatory of Electricity Resources".

Hydrogen (H2) technologies are expected to play a key role in the transition from a fossil-fuel based to a more sustainable, low-carbon energy systems (Carvalho et al, 2010). However, as for the other energy technologies, the hydrogen ones are not risk free. In this study, the technological risks associated to H2 technologies are identified, characterized and quantitatively analyzed. In this context, first an H2 energy chain is set up and afterwards its accident risk is compared against fossil fuels, hydropower and selected new renewables technologies. The comparison is made trough risk indicators (e.g. fatality rate) normalized by the unit of energy produced (e.g., GWeyr).

Data

Historical accidents related to hydrogen (H2), causing at least 1 consequence (e.g., 1 fatality, 1 injury, etc.) have been collected for the time period 1990-2014 for both OECD and EU28 country groups. Because of yet incomplete data, the years 2015 and 2016 have been neglected in the analysis. Moreover, we have chosen 1990 as a lower boundary, since before this year the use of hydrogen was a niche market.

In this study, a full-chain approach has been considered, since accidents are not occurring only during the energy production. For this purpose, a H2 energy chain has been built considering the following stages:

- **Production**, where only accidents related to by-product H2, e.g., through a chlor-alkali process, are considered, since main-product H2 is used for energy storage. Furthermore, under the condition that only accidents directly triggered by H2 are taken into account, no accidents related to production (as by-product hydrogen) are considered in the analysis. In fact, due to lack of information, it has been assumed that all consequences of an accident are bore by the main product of the industry that by-produce H2.
- **Transportation**
- **Storage**
- **Use**, which considers H2 related accidents during the direct use of H2 for electricity/heat production
- **Other End Use**, which gathers all other H2 uses with the reservation to be equivalent with an electricity/heat production (e.g., H2 Cooling)

Based on the aforementioned conditions H2 related accidents have been collected from different industrial databases, e.g., NRC, ARIA, FACTS, HINTS, HIAD.

H2 Energy Chain	Accidents/ Fatalities	Accidents/ Injuries	Accidents/ Evacuees
OECD	17/38	62/361	16/11554
EU28	5/18	26/178	9/4355

Summary of the numbers of accidents and associated consequences for the H2 energy chain collected in this study for OECD and EU28 countries in the time period 1990-2014.

Method

The risk indicators estimated for comparison purposes are defined as the ratio between the aggregated numbers of types of consequences, e.g., fatalities, in the time period 1990-2014 and the total energy production (e.g., GWeyr) in the same time period:

$$Risk\ Indicator = \frac{Aggregated\ Consequences_{1990-2014}}{Total\ Production\ (GWeyr)_{1990-2014}}$$

Where the total production (GWeyr) has been estimated from the total production in kg of H2 (Source OECD: Brown, 2016; Source EU28: http://ec.europa.eu/eurostat/web/prodcom/data/database).

For EU28, the collected production data covers the period 1995-2014. Therefore, to estimate the complete production from 1990-2014, as a first approximation, the missing production data years (1990-1994) have been constructed by keeping the 1995 value constant. For OECD countries only the 2014 data point has been found. Therefore, two cases have been constructed:

- Maximum production bound, where the total production has been set to 25 years * OECD production in 2014.
- Minimum production bound, where the total production has been set to 1 year * OECD production in 2014.

H2 Energy Chain	Production (kg)
OECD (Min Production Bound)	1.03E+11
OECD (Max Production Bound)	2.58E+12
EU28 (1990-2014)	8.42E+10

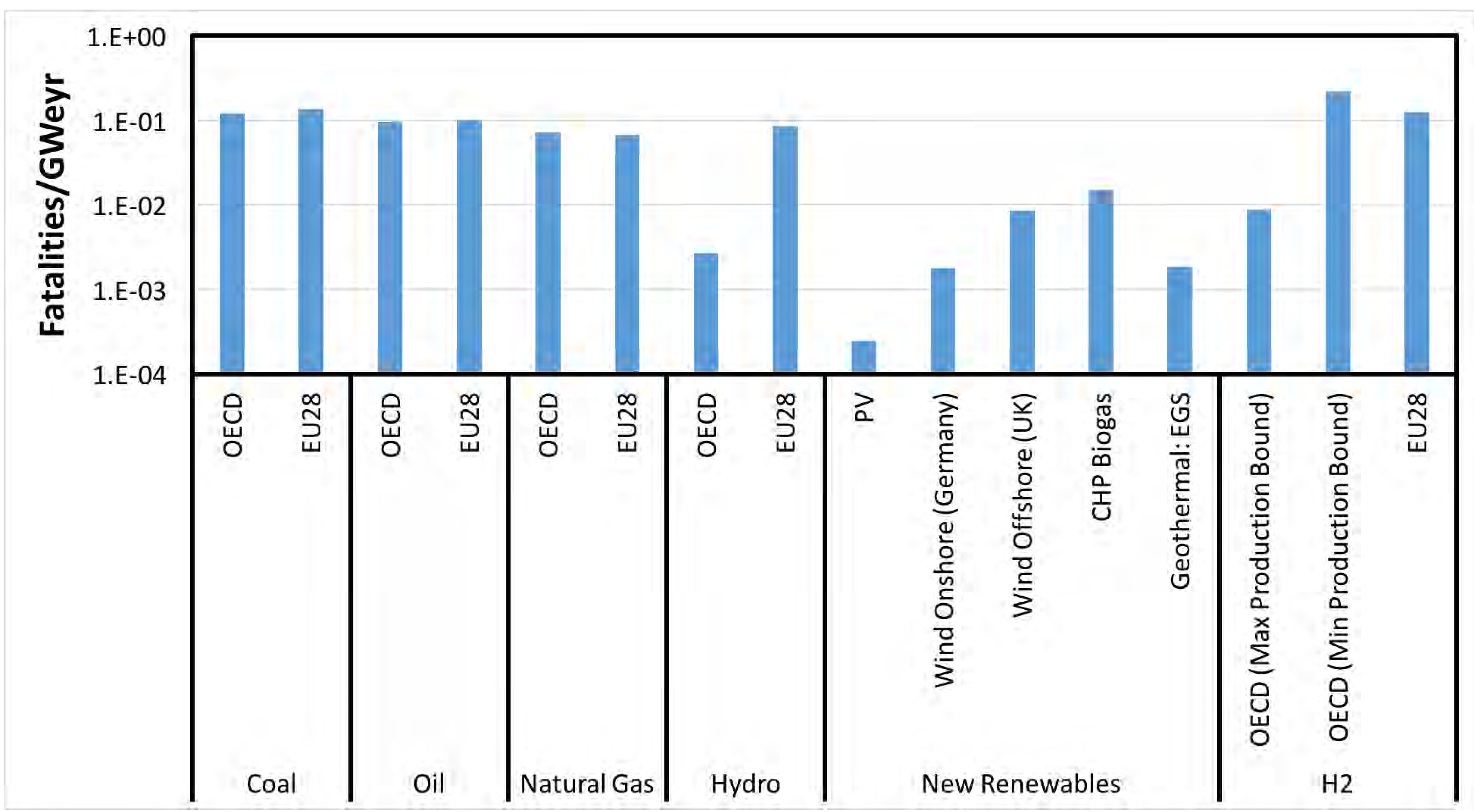
Summary of the H2 production collected for OECD and EU28 country groups in the time period 1990-2014.

Finally, in order to convert the H2 kg produced in GWeyr, the following has been used:

$$Production\ in\ GWeyr = Production\ in\ kg\ *\ \rho_{Energy} * ce$$

Where, ρ_{Energy} is the hydrogen energy density (3.8e-9 GWeyr, adapted from http://hypertextbook.com/facts/2005/MichelleFung.shtml), and *ce* is the hydrogen – electricity conversion efficiency (0.45, e.g., AFC Energy, 2016).

Preliminary Results for Fatality Rates



Fatality rates for fossil fuels, hydropower, new renewables and H2 energy chains for both OECD and EU28 country groups. The risk indicators for the other energy chains are adapted from (Burgherr and Hirschberg, 2014)

- H2 for EU28 performs worse than new renewables, hydro and natural gas, while it is comparable with oil and coal
- H2 for OECD performs worse than new renewable energy chains, unless for Wind Offshore (UK) and also hydro (OECD), which are close to the H2 lower bound. The other energy technologies are in the region where the H2 risk indicator should lie. However, while the CHP Biogas risk indicator is close to the H2 lower bound, the one for Coal, Oil and Natural Gas chains are close to the H2 upper bound.

Conclusions

In this study a first of its kind comparative risk assessment for H2 accidents has been conducted. Preliminary results show that H2 for EU28 is comparable with the fossil energy chains, while for OECD countries the risk indicator should be generally higher than the selected new renewables and hydro technologies. In the next step the main focus should be on the update the existing accident and production data and also include non-OECD countries in the analysis.

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