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Potentials, costs, and environmental effects of electricity generation technologies.

Synthesis

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1. Background

As a basis for its “Energieperspektiven” (Energy Perspectives), as well as the technology monitoring mandated by the new energy law, the Swiss Federal Office of Energy (SFOE) regularly reviews the **potentials**, **costs,** and **environmental effects** of electricity generation technologies. This analysis includes not only technologies that are options for domestic generation, but also options that could be significant for future electricity imports (e.g., wave power and offshore wind turbines). In addition to conventional generation processes, new technologies are considered that are not yet market-ready. With these it is still not possible to know if they will achieve a breakthrough and contribute substantially to Swiss electricity supply (e.g., nuclear fusion).

More concretely, the present study by the Paul Scherrer Institute (PSI) – which has also been conducted within the framework of the SCCER SoE and SCCER BIOSWEET[1] – has investigated the following technologies: Large hydro, small hydro, wind (onshore and offshore), photovoltaic (PV), biomass, deep geothermal (petrothermal), wave and tidal, solar thermal, nuclear, thermal power plants burning coal and natural gas (including natural gas combined heat and power co-generation), fuel cells, and “new” technologies (including hydrothermal methanization of wet biomass, non-conventional geothermal technologies, nuclear fusion, and thermoelectric generation from stationary waste heat).

This study shows the potentials, costs and environmental effects for the timeframe from today to 2050. This work does not address the interplay of the various technologies through system effects, or their external costs (e.g., the health costs caused by air pollution, or uninsured costs due to potential accidents).

This synthesis offers a compact overview of the results of the study that are most important for Switzerland. For further information and background, please refer to the more extensive summary with technology-specific data sheets, and also the individual chapters of the report. The majority of the numbers given in this synthesis are valid for specific assumptions and conditions that can be found in the data sheets and technology chapters.

2. Exploitable potentials of the renewable energies through 2050

The following Table 1 shows the exploitable potentials for electricity generation from renewable technologies in Switzerland by the year 2050. The exploitable potential represents that share of the technical potential that fulfills ecological and economic criteria. Social criteria such as acceptance are partially considered here, but may change over time, and are therefore associated with large uncertainties. Nuclear and fossil power plants theoretically have an unlimited technical potential; their exploitable potentials depend on a wide array of boundary conditions, and have not been quantified here. Nuclear energy and coal plants are not seen as future options for generation in Switzerland based on political grounds/conditions. However, electricity from these and other technologies may be imported.

[1] Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE); Swiss Competence Center for Bioenergy Research (SCCER BIOSWEET).

Table 1: Exploitable potentials for renewable electricity generation in Switzerland (in TWh/a).

Technology	Production 2015/2016	2035	2050
Large hydro[2]	32.7	32.7-34.0	32.7-34.0
Small hydro[3]	3.5	4.3-5.5	4.3-5.5
Wind energy	0.1	0.7-1.7	1.4-4.3
Photovoltaic[4]	1.1	5.5-16	11-19
Wood-fired cogeneration	0.1	0.1-0.6	0.1-1.1
Agricultural biogas	0.1	0.1-0.7	0.1-1.3
Deep geothermal	Not available	Still not seen as available on a large scale	4.5 (target)

The table above shows the exploitable electricity generation potential of each technology; this consists of the current generation plus the exploitable potential increase.

Among the renewable energy resources in Switzerland, **PV installations** show the greatest potential for increasing generation by 2035 and 2050, even when only the rooftop installations considered in this study are taken into account, and the bandwidth is relatively large. In contrast to other renewables, PV installations are generally facing less social opposition and a greater exploitation of their technical potential appears more realistic. It must also be considered that successful integration of large amounts of intermittent PV generation from decentralized installations requires appropriate measures for system integration. **Wind energy plants** also show a substantial potential for increase by the two reference years 2035 and 2050. Over the long term (2050) generation from **deep geothermal** could have a considerable potential, although this option is associated with great technical uncertainties. Over the medium term (2035), it appears that deep geothermal will not be available on a large scale due to the currently existing technical, economic, and social barriers (particularly seismic risks). The table above shows two technologies for **generation from biomass** which could be interesting for Switzerland by 2035 and 2050. At the present only a small part of the waste manure from agriculture is used as energy feedstock. For woody biomass, a part of the wood that today is used only for heat supply can also be used for additional electricity through cogeneration. For both woody and moist biomass, it is worth considering that these energy carriers can also be used as wood pellets or biogas either in the heat or transport sectors, depending on where the economics are better, based on the logistical and energy policy conditions (CO_2 taxes, etc.). That is, different uses compete for the same biomass potential. The potential for municipal waste incineration and wastewater treatment plants have not been presented in this summary, as their potential is small. In general, the efficiency of these plants can be increased thanks to new technologies. **Large hydro** power plants also have a certain potential for growth. The future development of hydro power mostly depends on the economic and political conditions. Substantial technological advance can no longer be expected, but there can be certain efficiency increases with plant renovations. The generation potential from **small hydro** power plants is relatively small, but not

[2] Production has been reduced by 1260 GWh/a, based on current legislation ("Gewässerschutzgesetz").
[3] The Swiss Federal Office of Energy assumes an additional potential of 1.3 to 1.6 TWh/a.
[4] The numbers are valid for rooftop PV installations; the sustainable potential for installations on facades is estimated at 3 to 5.6 TWh/a. Open-ground installations are not taken into account due to social constraints.

negligible. Their further deployment will mainly depend on state support and social acceptance, because this electricity is usually expensive and new power plants often encounter public resistance.

3. Generation costs

The two following tables show the current and future generation costs for the most important types of power. Table 2 shows generation costs for renewables (primarily in Switzerland). Table 3 summarizes generation costs for conventional (fossil and nuclear) power plants, more likely to be built abroad than in Switzerland[5]. More detailed generation costs for all technologies are part of the main report. The generation costs have been calculated based on the *levelized cost of electricity (LCOE)* methodology, which discounts future costs, and contains the following components: capital costs for construction, operating costs over the plant life (fuel costs, and fixed and variable operation and maintenance costs), and decommissioning costs at the end of life. Capital and operating costs for all technologies have been discounted using an interest rate of 5%. The bandwidths shown reflect the variability of the generation costs based on location-specific conditions (e.g., annual yields of PV and wind power plants), technology characteristics (e.g., power plant efficiencies and performance), as well as biomass costs. The costs of CO_2 emissions and other external costs have not been considered[6]. The generation costs include a heat credit[7] for biomass and natural gas cogenerators, fuel cells and agricultural biomass plants; these technologies are generally operated based on their heat demand, so that a part of the heat they produce can be either sold or used on site.

While the costs for electricity from hydropower, wood cogeneration, agricultural biomass and fossil generation increase through 2050, the generation costs for photovoltaics drops by half, and for wind power somewhat less, so that by 2050 they roughly achieve the cost level of large hydro. The generation costs for electricity from gas combined cycle plants will be – without consideration of CO_2 costs – approximately as high as for small PV plants or wind energy. Without consideration of CO_2 costs, also electricity from coal power plants will be comparatively inexpensive in the future.[8]

[5] Construction of new nuclear power plants in Switzerland is forbidden according to the updated law on nuclear energy after the positive referendum regarding the Swiss energy strategy 2050 on 25th of May 2017. Whether natural gas combined cycle power plants will be operated in Switzerland will depend on the future structure of the electricity market and Swiss climate policy.
[6] The cost of CO_2 certificates is currently very low, and therefore neglected. An estimate of future CO_2 prices was outside the framework of the present study.
[7] The economy of a plant that produces both electricity and heat is essentially influenced by the revenue from the heat produced (offset), which is often referred to as the heat credit.
[8] At a CO2 price of 10 CHF/ton CO_2, electricity generation costs of natural gas and coal power plants increase by about 0.5 Rp./kWh and 1 Rp./kWh, respectively (according to estimates of the SFOE).

Table 2: Generation costs for newly built renewable power plants in Switzerland and offshore wind abroad (in Rp. /kWh).

Technology	**New plants**		
	Today	**2035**	**2050**
Large hydro[9]	7-30	7-30	7-30
Small hydro	12-28	14-33	14-34
Wind - Switzerland	13-21	10-17	9-15
Wind - offshore	13-27	12-23	10-20
Photovoltaic: 10 kW 1000 kW	18-31 8-13	9-22 4-10	8-19 3-9
Wood cogeneration[10]	18-36	18-41	18-45
Agricultural biogas[11]	20-49	18-50	16-51
Deep geothermal[12]	Not available	16-58	13-47

Table 3: Generation costs for newly built fossil and nuclear power plants, primarily in Europe (in Rp./kWh)[13].

Technology	**New plants**		
	Today	**2035**	**2050**
Nuclear	5.1-12.5[14]	5.1-12.5[15]	Not available[16]
Gas combined cycle	10.8-12.3	12.9-14.2	14.5-16
Gas combined cycle with CO_2 sequestration	Not available	15.3-17.7	17.3-19.8
Nat. gas cogen: 10 kW_{el} 1000 kW_{el}	22-45 10-15	23-45 12-17	23-45 17-20
Fuel cells: 1 kW_{el} 300 kW_{el}	65-125 22-70	23-64 14-37	19-46 13-24
Coal plants (foreign)	3.9-8.3	4.2-8.7	4.4-8.9
Coal with CO_2 seques-tration	Not available	6.3-10.4	5.5-10.6

[9] Run of river and storage dam power plants have not been distinguished as specific data is lacking. For the existing plants the production costs lie in the range of 2 to 10 Rp./kWh.
[10] Including heat credit.
[11] Including heat credit.
[12] Excluding heat credit, as it was judged to be difficult to find purchasers for the large amount of heat.
[13] Fuel costs (natural gas and coal) used here are supposed to be valid for Switzerland.
[14] New Gen III/III+ reactors as primarily built in Asia (China, South Korea) today.
[15] Gen III(+) or Small modular reactors (SMR).
[16] Based on the deficit of dependable data, no estimates are possible for Generation IV in the year 2050.

The present study has made assumptions about the future price trajectory for fossil energy carriers, which are most relevant for the coal and natural gas combined cycle plants, but also for the cogeneration plants. These assumptions are based on data from the World Energy Outlook 2016 from the International Energy Agency (IEA). The Table 4 shows the assumed price trajectories in CHF per MWh for the Swiss industrial sector, excluding taxes. The prices for coal and natural gas, the most important energy carriers for conventional generation, are supposed to increase by about half by the year 2050.

Table 4: Assumptions for future industrial energy prices based on IEA data (in CHF per MWh). [17]

Energy carrier	2015	2020	2025	2030	2035	2040	2045	2050
Coal	13.1	18.4	19.0	19.7	20.2	20.6	21.0	21.4
Light oil	45.6	53.5	63.9	73.5	78.2	82.3	85.1	87.4
Heavy oil	31.0	50.0	56.5	62.0	64.6	66.9	68.5	69.8
Natural gas	55.7	57.1	64.6	71.7	74.6	76.9	78.9	80.5

[17] The prices in the report are in CHF_{2015} per GJ. It also includes energy prices for Europe and other sectors (household, transport).

4. Environmental aspects

The quantification and evaluation of the environmental burdens associated with electricity generation are based on the Life Cycle Assessment (LCA) methodology, and contain the full energy chain, including production, delivery, infrastructure, etc.

Greenhouse gas emissions (GHG), which cause the associated effects on climate change, are used in the present work as the primary environmental indicator for current and future electricity generation technologies. Further environmental burdens of current technologies are presented and discussed in the main report. The LCA method is used to quantify the environmental impacts of normal operation by power plants and fuel supply chains. The potential consequences of severe accidents are not considered. The method does not allow the measurement of local and site-specific environmental impacts, for example the effects of small hydro plants on local ecosystems. The following table shows the greenhouse gas emissions for generation by current and future technologies. The bandwidths shown reflect variability related to local factors (e.g., the annual yields of PV and wind plants in Switzerland), technology characteristics (e.g., efficiency and power plant performance) and fuel properties. Emissions from cogeneration and fuel cells are allocated according to the exergy[18] of the electricity and heat produced.

Generation from hydro and nuclear power plants, as well as wind turbines, causes the lowest GHG emissions. Greenhouse gas emissions of electricity from natural gas combined cycle and coal power plants could be substantially reduced in the future by means of CO2 sequestration. It can be assumed for most technologies that the greenhouse gas emissions will decrease by the year 2050. The exceptions are hydro power and nuclear energy – where there is practically no potential for reduction. Instead, decreasing uranium ore concentrations could increase the environmental burdens of uranium production and nuclear power. Similar, lower availability of conventional fossil resources could also lead to higher emissions from natural gas and coal-fired power plants in the future.

[18] Exergy reflects the quality of energy; electricity has a higher energetic value than heat, especially when low temperature heat is considered.

Table 5: Greenhouse gas emissions due to electricity generation with different technologies (in g CO_2eq/kWh), today and in 2050.

Technology	New plant	
	Today	**2050**
Hydro - Run of river	5-10	5-10
Hydro - Storage dam	5-15	5-15
Small hydro	5-10	5-10
Wind - Switzerland	8-27	5-30
Wind - Offshore	8-16	5-20
Photovoltaic: Multi-crystalline Monocrystalline Thin film	39-69 62-109 25-43	7-45 11-71 8-30
Wood combustion & gasification	10-120	10-100
Agricultural biogas plants[19]	150-450	Not available
Deep geothermal	Not available	27-84
Nuclear energy	10-20	5-40
Gas combined cycle (GCC)	387-400	346-363
GCC with CO_2 sequestration	Not available	70-100
Gas cogeneration: 10 kW_{el} 1000 kW_{el}	583-633 459-500	546-601 423-468
Fuel cells: 1 kW_{el} 300 kW_{el}	560-780 370-650	440-570 340-450
Coal plants (foreign)	823-1022	734-850
Coal plants with CO_2 sequestration	Not available	34-214

[19] The greenhouse gas emissions from biogas plants are strongly dependent on potential methane losses during the digester fermentation process, which have large uncertainties as indicated by the correspondingly large bandwidths given. No reliable LCA results are available for 2050.