Comparative environmental assessment of current and future electricity supply technologies for Switzerland

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ABSTRACT

The environmental performance of a portfolio of eighteen technologies for electricity generation including renewable, fossil, and nuclear systems was analyzed for two reference years 2000 and 2030. The assessment covers large centralized and smaller decentralized power plants in Switzerland and few other European countries (for electricity imports). Evolutionary technology development was assumed between today and 2030.

Full life cycle inventories were established for all energy chains, using ecoinvent as the background inventory database. The average European electricity mix in 2030 was adapted using a business as usual scenario. The environmental assessment was part of a more comprehensive interdisciplinary sustainability evaluation using a multi-criteria decision analysis (MCDA) approach.

Results from this evaluation for the environment area alone are herewith compared using Eco-indicator'99 as representative LCIA method as well as external cost assessment. In general the rankings from different aggregation methodologies converge when considering common indicators. However, putting different emphasis or weight on impact categories and individual indicators introduces variation in the ranking. Superior environmental performance of hydro power is ascertained by all approaches. Nuclear follows hydro as top performer based on Eco-indicator 99 (H, A) and external costs. Fossil systems score worst and biomass shows mostly worse performance than other renewables.

Introduction

Options for near future Swiss electricity supply are currently one of the main topics in the energy policy debate in Switzerland. While the growth of total energy demand per capita has practically stopped since the beginning of this century, the electricity demand per capita is steadily growing [1]. It is expected that the role of electricity will be even more important for the future service economy. However, in the next two decades the Swiss nuclear power plants will be phased out and the electricity imports from France will no longer be secured. Therefore, major decisions concerning future electricity supply in Switzerland need be taken now. A project coordinated and supported by a major Swiss energy supplier (Axpo Holding AG) established an interdisciplinary sustainability evaluation framework for the comprehensive assessment of current and future (2030) electricity-generating systems. In addition to PSI, the participants included the University of Stuttgart, the Centre for Energy Policy and Economics (CEPE) at the Swiss Federal Institute of Technology Zurich (ETHZ), and BAK Basel Economics. Economic, environmental, and social aspects were covered in the study. This paper focuses on the comparison of environmental impacts of electricity systems, one of the tasks under PSI's responsibility.

Goal and Scope

The broad portfolio of eighteen technologies for electricity generation includes renewable, fossil, and nuclear power plants with their associated energy chains. The environmental performance was analyzed for two time frames around the reference years 2000 (representing currently best available technology) and 2030. The technology portfolio contains both large centralized power plants and smaller decentralized units in Switzerland and few other European countries (for electricity imports). Small combined heat and power units burning natural gas or gasified biomass were assessed besides base-load and mid-load large power plants. Evolutionary technology development was assumed to take place between today and 2030 for all reference power plants. The LCI database ecoinvent v1.2 was used as background for year 2000 [2, 3]. An average European electricity mix in 2030 was defined in order to reflect a business as usual development of the economy. Table 1 and Table 2 give an overview of the technologies included in the assessment for year 2000 and 2030, respectively.

Table 1: List of power technologies and main characteristics, year 2000.

Energy source	Nuclear	Nuclear	Hard coal	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Hydro power
Technology	Pressure water reactor, Generation II	Pressure water reactor, Generation II	Supercritical steam cycle (SC), base load	Combined Cycle (CC), base load	Combined Cycle (CC), mid load	Combined Cycle (CC), base load	Combined Heat & Power (CHP)	Solid Oxide Fuel Cell (SOFC)	Run-of-river
Capacity el. [MW_{el}]	730	1300	509	400	400	400	0.2	0.2	51
Capacity th. (CHP) [MW_{th}]	-	-	-	-	-	-	0.3	0.2	-
Location	Switzerland (CH), Beznau	France (F), Cattenom	Germany (D), Rostock	Switzerland, Birr	Switzerland, Birr	Italy (I), Naples	Switzerland, Baden	Switzerland, Baden	Switzerland, Wildegg-Brugg
Operating time [full load hours per year]	8000	6300	7000	8000	4000	8000	4500	4500	5720
Efficiency electric [%]	32.0	34.0	43.2	57.5	55.5	55.5	32.0	40.0	88.9
Lifetime [a]	40	40	30	25	25	25	20	5	80

Energy source	Hydro power	Biogas	Synthetic Natural Gas (SNG)	Wind power	Wind power	Wind power	Photovoltaic	Photovoltaic	Geothermal
Technology	Reservoir	Combined Heat & Power (CHP)	Combined Heat & Power (CHP)	Onshore wind park, 4 turbines	Onshore wind park, 50 turbines	Offshore wind park, 80 turbines	multicrystalline-Si panel, roof-top	amorphous-Si, roof top	Enhanced Geothermal System (EGS)
Capacity el. [MW_{el}]	53	0.1	0.2	4x0.85	50x2	80x2	0.02	0.01	3
Capacity th. (CHP) [MW_{th}]	-	0.1	0.3	-	-	-	-	-	-
Location	Switzerland, Ilanz/Panix	Switzerland, Baden	Switzerland, Baden	Switzerland, Mt. Crosin	Germany (D), North Sea coast	Denmark (DK), HornsRev	Switzerland, Baden	Switzerland, Baden	Switzerland, Basel
Operating time [full load hours per year[	2476	7000	4500	1250	2500	3750	850	850	7000
Efficiency electric [%]	89.0	36.0	32.0	n.s.	n.s.	n.s.	14.8	7.3	11.3
Lifetime [a]	150	15	20	20	20	20	30	20	30

Table 2: List of power technologies and main characteristics, year 2030.

Energy source	Nuclear	Nuclear	Hard coal	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Hydro power
Technology	European Pressure water reactor (EPR), Generation III	European Pressure water reactor (EPR), Generation III	Integrated Gasification Combined Cycle (IGCC)	Combined Cycle (CC), base load	Combined Cycle (CC), mid load	Combined Cycle (CC), base load	Combined Heat & Power (CHP)	Solid Oxide Fuel Cell (SOFC)	Run-of-river
Capacity el. [MW_{el}]	1500	1500	450	500	500	500	0.2	0.2	51
Capacity th. (CHP) [MW_{th}]	-	-	-	-	-	-	0.21	0.11	-
Location	Switzerland (CH), Beznau	France (F), Cattenom	Germany (D), Rostock	Switzerland, Birr	Switzerland, Birr	Italy (I), Naples	Switzerland, Baden	Switzerland, Baden	Switzerland, Wildegg-Brugg
Operating time [full load hours per year[	8000	8000	7000	8000	4000	8000	4500	4500	5720
Efficiency electric [%]	33.8	33.8	51.5	63	61	61	42	52	88.9
Lifetime [a]	60	60	30	25	25	25	20	15	80

Energy source	Hydro power	Biogas	Synthetic Natural Gas (SNG)	Wind power	Wind power	Wind power	Photovoltaic	Photovoltaic	Geothermal
Technology	Reservoir	Combined Heat & Power (CHP)	Combined Heat & Power (CHP)	Onshore wind park, 5 turbines	Onshore wind park, 50 turbines	Offshore wind park, 50 turbines	multicrystalline-Si panel, roof-top	amorphous-Si, roof top	Enhanced Geothermal System (EGS)
Capacity el. [MW_{el}]	53	0.2	0.2	4x2	50x4.5	80x20	0.02	0.01	36
Capacity th. (CHP) [MW_{th}]	-	0.15	0.21	-	-	-	-	-	-
Location	Switzerland, Ilanz/Panix	Switzerland, Baden	Switzerland, Baden	Switzerland, Mt. Crosin	Germany, North Sea coast	Denmark (DK), North Sea	Switzerland, Baden	Switzerland, Baden	Switzerland, Basel
Operating time [full load hours per year[	2476	7500	4500	1500	2700	4000	850	850	7000
Efficiency electric [%]	89.0	41.7	42	n.s.	n.s.	n.s.	19.8	13.7	11.3
Lifetime [a]	150	15	20	20	20	20	30	20	30

The modeling of the current Swiss nuclear chain with the power plant in Beznau is based on the LCA of the average Swiss pressure water reactor [4]. Specific characteristics of the reactor in Beznau are taken into account. The analysis of the current French nuclear chain with the reactor in Cattenom builds on the LCA of the French nuclear chain in [4]. Reference technology in year 2030 is the European Pressurized Reactor (EPR) at the same two sites. Fuel enrichment is modeled with centrifuges only.

The hard coal power plant in Rostock, Germany, one of the most modern operational German plants today, served as reference plant in year 2000 for (assumed) electricity imports to Switzerland. Plant-specific emission data were available for the key emissions SO_2, NO_x, and particulate matter. Other emission data as well as the upstream chain were modeled along with the average German hard coal energy chain [4]. Future reference technology is an IGCC plant. Higher share of imported steam coal in Germany in 2030 was taken into account.

Reference technology for current large natural gas power plants is a 400 MW_{el} Combined Cycle unit [4]. The analysis differentiates between base load and mid load operation on the one hand, and location of the plants in Switzerland and Italy on the other hand. The upstream chains of the units are modeled with the average country-specific natural gas supply [4]. Technology development until 2030 is taken into account with higher efficiencies.

Combined heat and power production (CHP) with natural gas as fuel is represented by a 200 kW_{el} Lambda1-Motor including a three-way catalytic converter [4], and a 200 kW_{el} Solid Oxide Fuel Cell (SOFC) [5, 6], respectively. The analysis of the current CHP-motor is extrapolated from [4] and uses the average Swiss natural gas supply. Technology developments of SOFC until 2030 are characterised by higher efficiencies, reduced emissions, and longer lifetime of the components.
Material and energy consumption for the construction of the run-of-river power plant Wildegg-Brugg is reported in [7]. Lifetime is assumed to be 80 years [4]. The hydro plant Illanz/Panix is used as the reference reservoir site. Plant-specific data for material and energy consumption for the construction are used for the LCI. Lifetime of the dam is assumed to be 150 years [4]. The same hydro plants represent the reference technologies in 2030.
Biogas from agricultural manure and Synthetic Natural Gas (SNG) from forest wood gasification are assumed to fuel CHP units. The modeling of the biogas fermentation in year 2000 is based on [8]. Basis for the production of SNG via wood gasification is the assessment of a 50 MW_{th} future demonstration plant [9]. In this study, the plant is assumed to be located at a proper location in Switzerland with sufficient wood available within a radius of 25 km. The modeling of the CHP units for both biofuels is based on [4]. A commercialized methanation plant with doubled capacity and increased efficiency as well as improved CHP units for biogas and SNG combustion reflect the expected technology development until 2030. The change of CHP technology for biogas from ignition gas engine to a unit with exhaust gas recirculation reduces NO_x emissions by a factor of 20.
Photovoltaic (PV) reference technology in year 2000 for crystalline silicon is the laminated, integrated slanted-roof multicrystalline-Si module in [4], which is adapted to the electricity production of 850 kWh kW_p^{-1} a^{-1} at the reference site of Baden, Switzerland. The amorphous silicon reference module (Module Uni-Solar SHR-17) for year 2000 is assumed to be installed at the same site. Its LCI is based on [10]. Not only efficiency increase for the PV-cells as such, but also reduced energy demand in key production steps of the PV chains are taken into account for the modeling of the future reference PV units.
The Nordex N50 800 kW wind turbine is used as current reference technology for onshore wind power in Switzerland [4], located at Mt. Crosin, Switzerland, with a capacity factor of about 0.14. Vestas' V80 2 MW turbine serves as reference technology for onshore wind power in year 2000 in Germany. The assessment is based on [11], adapted to the assumed location. The capacity factor for a generic site near to the coast of the North Sea is assumed to be 0.29. Offshore wind power in the year 2000 is represented by the wind park HornsRev in the Danish part of the North Sea. The whole park consists of 80 Vestas V80 turbines with monopile steel foundations. The modeling of the turbine and the grid connection is based on [11] and [12], respectively. Future wind turbines with higher capacities are assumed to be located at the same or similar sites.
The geothermal reference power plant for year 2000 is an Enhanced Geothermal System (EGS), also known as Hot-Dry-Rock (HDR), under construction in Basel, Switzerland. Water is circulated in a closed cycle down to a depth of 5500 m. Due to the relatively low electric efficiency of 11.3%, the plant produces substantial waste heat, but no cogeneration has been assumed here. The inventory of this system is mainly based on [4, 13]. Future geothermal technology is modeled with a higher capacity of the plant, a higher flow rate of the geothermal circle, and reduced energy demand for drilling.

Results

Figure 1 and Figure 2 show results obtained applying Eco-indicator 99 (H,A) [14] to LCI results (per kWh) for the current and future technologies herewith analyzed. The decreasing scores correspond to decreasing LCI values for the expected/modeled improvements for most of the technologies: nuclear 13-23% reduction due to longer lifetime of power plants and higher burn-up; fossil 9-18% reduction basically due to increase of efficiency but also decrease of emissions of air pollutants; for biogas 35% reduction due to substantially reduced air pollutants and higher efficiencies; SNG 23% reduction due to total efficiency improvement (gasification process and CHP); about 40% reduction in PV technologies due to manufacturing energy requirements decrease as well as panel efficiency improvements; geothermal also shows a decrease of nearly 40%; and, 16% reduction in wind on-shore CH due to turbine technology improvement. Hydro exhibits basically the same scores, since the construction technology and efficiency do not change significantly. On the contrary, wind onshore and offshore in North Europe show higher score by 32% and 86%, respectively; in the first case because of different tower material hypothesized (concrete instead of steel), in the second case because of much larger machine and thus tower as well as larger foundations and increased distance to the shore with only slightly higher capacity factors than assumed for year 2000. However, the general ranking does not change between 2000 and 2030: hydro, nuclear and onshore wind in Germany show the best performance (i.e. the lower the score, the better the performance), followed (in the order) by other wind park sites, geothermal, and PV. Biogas and hard coal exhibit close values in both cases, and SNG still scores higher than them in 2030 due to the large land use for tree growing. In case the latter would be neglected with the argument of using an established, sustainable forestry, SNG would score better than biogas CHP and hard coal IGCC. Fossil gas systems score the highest for the high damage factor of the natural gas resource use assumed for EI'99 (H,A). In case fossil resources would not be weighted, natural gas systems would score lower than biofuels and hard coal, and biofuels would score the worst.

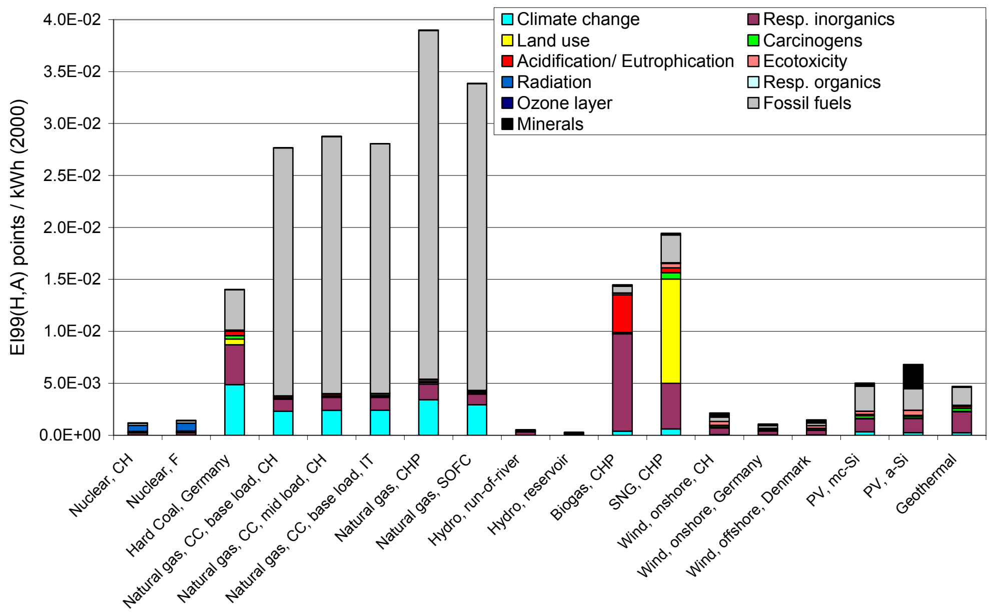

Figure 1: LCIA results for the reference technologies in year 2000 using Eco-indicator 99 (H,A).

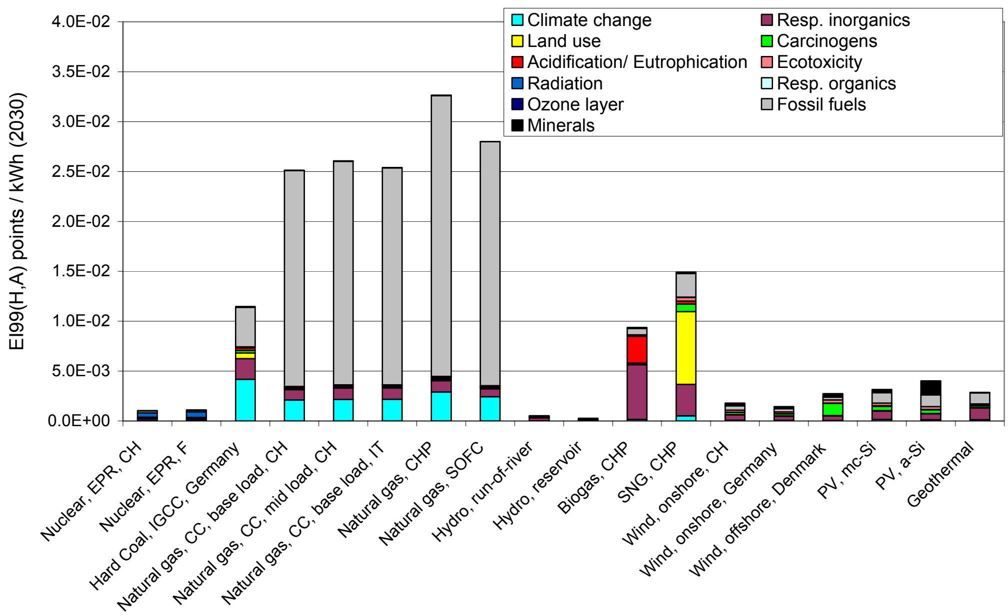

Figure 2: LCIA results for the reference technologies in year 2030 using Eco-indicator 99 (H,A).

Figure 3 and Figure 4 show the results obtained for external costs using average European damage factors from ExternE [15] applied to LCI cumulative results along with [16]. However, site-specific damage factors were used in the study. Results are partially similar to EI'99 (H,A): for 2030, lowest costs due to hydro power, followed (roughly in the given order) by wind, nuclear, biogas, PV, geothermal and SNG. Clearly higher costs are attributed to fossil systems due to the dominating contribution of CO_2 (damage factor 19 €$_{2000}$/tonne), although due to efficiency improvements and lower air pollution the costs decrease substantially compared to year 2000. The highest external costs are calculated for coal, due to its higher CO_2 emission rate compared to natural gas. Biofuels score better than fossil systems in both approaches; in EI'99 (H,A) the main reason lies in the valuation of fossil resources.

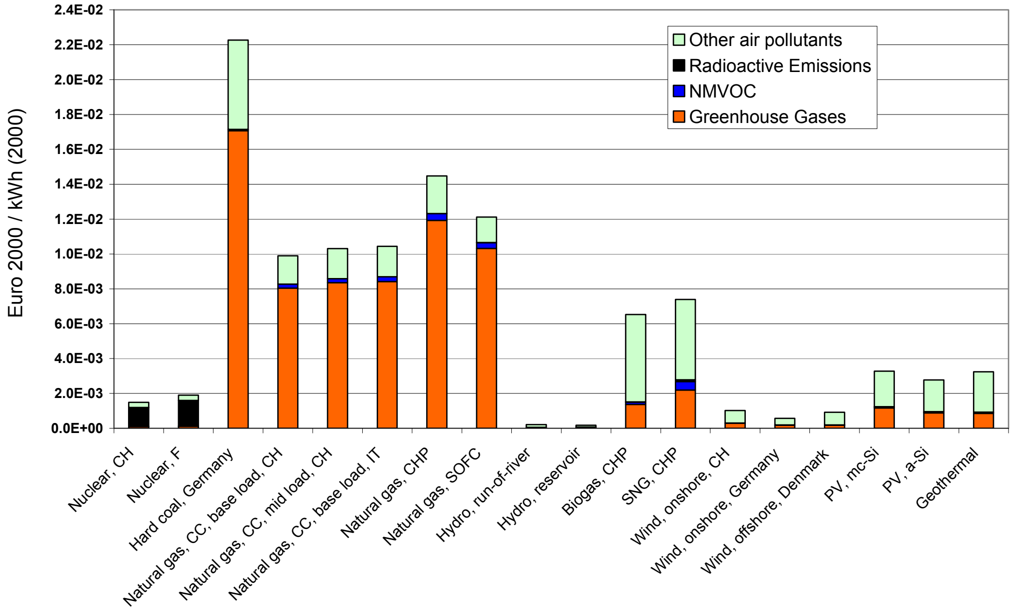

Figure 3: External costs of electricity production for the reference technologies in year 2000.

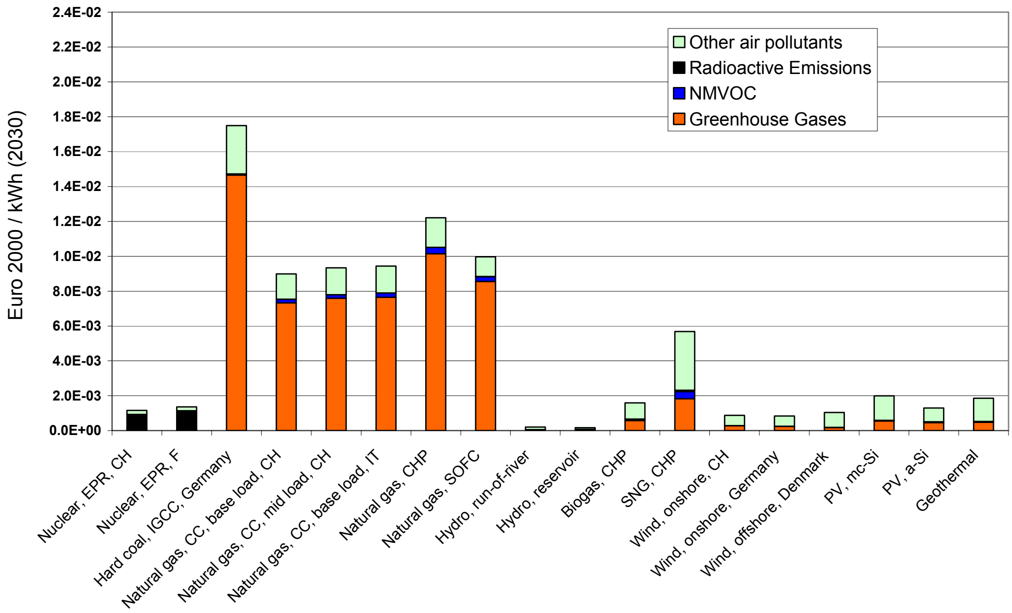

Figure 4: External costs of electricity production for the reference technologies in year 2030.

The environmental component of the MCDA sustainability framework comprises the following indicators: greenhouse gas emissions; consumption of fossil, mineral and uranium resources, grouped as "resources"; land use, ecotoxicity, acidification, eutrophication, and land contamination due to accidents, grouped as "impact on ecosystems"; radioactive and non radioactive waste, grouped as "wastes". When applying MCDA to the environmental component alone, hydro power shows again a superior performance. The results are quite differentiated for the other technologies. With equal weighting of the indicators, hard coal systems show the worst results for both time frames, consistently with external costs and results of EI'99 (H,A) without accounting for resources. Among the so called "new renewables", geothermal and onshore wind power from Germany perform best. Nuclear score is in the middle range comparable to natural gas CC and PV. Naturally, the ranking changes with weighting profiles, depending on stakeholder preferences on individual criteria.

Conclusions

The ranking of the assessed technologies concerning their environmental performance is relatively stable with the used assessment methods and perspectives shown. Nonetheless, application of other LCIA methods may provide other perspectives which would be useful for further elaboration of the robustness of the ranking. Furthermore, differential weighting on single damage categories or indicators, depending on different stakeholder values, can result in rank switches among the technologies. Anyway, explicit consideration of economic and social aspects besides environment is necessary for a truly complete sustainability assessment and ranking reflecting full set of preferences.

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