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Synthesis Report

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Executive Summary

This synthesis report provides an overview of primary electricity supply sources, including power generation potentials and costs as well as the associated environmental burdens of electricity production in Switzerland. It gives a synthesis of the main findings and selected deep-dives into key technologies supporting the transition of the Swiss energy system, namely solar photovoltaics (PV), hydropower, biomass and deep geothermal energy generation.

In general, Swiss renewable resources seem to be sufficient, but the transition of the Swiss energy system towards 100 % renewables and net-zero CO_2 emissions will only succeed if the domestic electricity generation potential for all renewables can be exploited to a large extent. While solar PV exhibits the largest potential by far and must be quickly expanded, it is important to increase the generation from other renewables in parallel, since such a combination of different primary energy resources and technologies allows synergies to be exploited, reduces lock-in risks, and facilitates integration of renewables by increasing system flexibility.

Estimates for annual PV generation based on existing buildings vary widely and are on the order of 20 TWh to more than 50 TWh per year. In addition, modules installed on other existing infrastructure, or on green field sites could generate substantial amounts of electricity. In this context, the challenge is therefore not so much the overall amount of PV generation but its intermittent character with distinct peaks at noon and in summer. Installation of modules in the mountains, where higher irradiation levels are generally available, could change this production pattern and shift the summer peak to winter to some extent. Other resources and generation technologies – wind, biomass and hydropower – exhibit much lower potentials for additional generation, on the order of a few TWh per year each. Nevertheless, these technologies are important from a systemic perspective because they have different characteristics than PV and can be operated in systemically useful ways. In contrast, deep geothermal power generation in Switzerland is still associated with large uncertainties, and whether it will contribute to future power supply is uncertain – further research and development should be carried out, since deep geothermal power is a base-load generation option that can also generate useful heat.

All these renewables are compatible with stringent climate policy goals, also including indirect emissions from a life cycle perspective. However in the case of biomass sustainable practices in forestry, land management and agriculture must be ensured. In addition to renewables, natural gas power plants with carbon capture and storage would qualify as low-carbon-technology. However, permanent geological storage of CO_2 remains a challenge, especially within Switzerland.

Average electricity generation costs in Switzerland are likely to increase in the future. Despite substantial reductions in the generation cost of PV (and to some extent wind power) that can be expected over the next decades, it is still very likely that electricity from new PV modules, wind turbines, hydro and biomass power plants will be more expensive than from existing hydro and nuclear power plants. In case of PV, costs could be reduced by profiting from economies of scale, i.e. installation of large plants. In addition, and especially for wind power, streamlining administrative and planning procedures would drive costs down. Operating a system predominantly based on renewables will also require expanding energy storage and grid infrastructure, which will represent additional expenses beyond pure generation costs.

Additional challenges associated with the large-scale exploitation of renewables in Switzerland must not be forgotten: renewables often face strong local opposition, whether against installation of new wind turbines, increasing the heights of existing reservoir dams, or due to perceived risks in the context of geothermal generation. However, there are not only challenges, but also opportunities and co-benefits that come with the expansion of renewables: dependence on imported energy carriers and associated risks would decrease, the Swiss high-tech sector would profit, and more value creation would take place at the regional and national levels.

Acronyms and Abbreviations

ARE	Amt für Raumentwicklung (Federal Office for Spatial Development)
BAPV	Building Attached Photovoltaic
BFE	Bundesamt für Energie (Swiss Federal Office of Energy)
BIPV	Building Integrated Photovoltaic
BOS	Balance of System
CAGR	Compound Annual Growth Rate
CC	Combined Cycle
CCS	CO_2 Capture and Storage
CFC	Chlorofluorocarbon
CHF	Swiss Franc (1 CHF = 100 Rp.)
CHP	Combined Heat & Power
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CSP	Concentrated Solar Power
CTU	Comparative Toxic Unit
DC	Direct Current
EEG	Erneuerbare-Energien-Gesetz
EGS	Enhanced Geothermal Systems
EOL	End-Of-Life
EPFL	École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology in Lausanne)
ETHZ	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology in Zürich)
EUR	Euro (1 EUR = 100 Euro cents)
FC	Fuel Cell
FOM	Fixed Operation and Maintenance
GHG	Greenhouse Gases
GSA	Global Sensitivity Analysis
GWp	Gigawatt Peak
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JASM	Joint Activity Scenarios & Modelling
KEV	Kostenorientierte Einspeisevergütung
KVA	Kehrichtverbrennungsanlage
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
LEA	Laboratory for Energy Systems Analysis
LHP	Large Hydropower
MAD	Mean Absolute Deviation
MC	Molten Carbonate
MSW	Municipal Solid Waste

MW_{el}	Megawatt electric
MWI	Municipal Waste Incinerator
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
NMVOC	Non-Methane Volatile Organic Compounds
O&M	Operation and Maintenance
ORC	Organic Rankin Cycle
PA	Phosphoric Acid
PE	Polymer Electrolyte
PM	Particulate Matter
PPA	Power Purchase Agreement
PSI	Paul Scherrer Institut
PV	Photovoltaics
PWR	Pressurized Water Reactor
R&D	Research and Development
Rp.	Rappen (100 Rp. = 1 CHF)
SCCER	Swiss Competence Center for Energy Research
SCCER Biosweet	SCCER Biomass for Swiss Energy Future
SCCER HaE	SCCER Heat and Electricity Storage
SCCER Mobility	SCCER Efficient Technologies and Systems for Mobility
SCCER-SoE	SCCER Supply of Electricity
SFOE	Swiss Federal Office of Energy
SHP	Small Hydropower
SO	Solid Oxide
SURE	Sustainable and Resilient Energy for Switzerland
SWEET	Swiss Energy Research for the Energy Transition
VOM	Variable Operation and Maintenance
WEO	World Energy Outlook
WWTP	Waste Water Treatment Plant

kWh	kilowatt-hour
GWh	gigawatt-hour, 1 GWh = 10^6 kWh
TWh	terawatt-hour, 1 TWh = 10^9 kWh
PJ	peta-joule, 1 PJ = 0.277 TWh, 1 TWh = 3.6 PJ

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1 Introduction

Low-carbon electricity will be the central pillar of the transformation of the Swiss energy system towards the goal of carbon neutrality by 2050. Research activities within the SCCER Supply of Electricity have focused on supporting this transformation in the electricity sector. The results of this research are of immediate interest for the Swiss Federal Office of Energy, as well as for scenario modeling of the Swiss energy system.

This synthesis report summarizes two major studies (Bauer et al., 2017; Bauer et al., 2019) that were commissioned by the Swiss Federal Office of Energy (SFOE), and funded by SFOE and the Swiss Competence Center for Energy Research (SCCER) – Supply of Electricity (SoE). The analysis serves the purpose of technology monitoring by the SFOE, and the results are used as technology performance inputs for the Swiss Energy Perspectives. Simultaneously, it has provided a core contribution to the research activities of Work Package 4 "Future Supply of Electricity" within the SCCER-SoE, and was used by other SCCERs, including Biomass for Swiss Energy Future (Biosweet), Heat and Electricity Storage (HaE), Efficient Technologies and Systems for Mobility (Mobility), and the Joint Activity Scenarios and Modeling (JASM).

1.1 Goal and Scope

This synthesis report provides a comprehensive evaluation and comparison of technology-specific potentials and costs of domestic electricity generation in Switzerland, as well as electricity imports from neighboring countries for selected technologies. The environmental performance is also evaluated for the technologies considered. Potentials, costs and environmental aspects are quantified for today (i.e. 2020), 2035 and 2050, which allows the use of this data to support the implementation and benchmark the actual status of the Swiss Energy Strategy 2050+ (Swiss Federal Office of Energy, 2020a). Future technology performance and associated potentials, costs and environmental burdens are estimated based on experience from relevant recent and current projects as well as use of learning curves, expert consultations and literature. Depending on the technologies, uncertainties in these estimates can be substantial. Therefore, as far as reasonable, the potentials, costs and environmental burdens are given ranges that reflect these uncertainties.

The present synthesis report provides a synopsis of key results, conclusions and recommendations. For in-depth coverage we refer to the two above-mentioned reports and a few other publications. Potentials, costs and environmental performance indicators are given for today and 2050, covering a broad portfolio of electricity generation technologies, including:

- Large hydropower (LHP): Capacities above 10 MW, including run-of-river, reservoir, and pumped storage power plants
- Small hydropower (SHP): Capacities below 10 MW, categorized by construction type or runoff medium
- Wind power: Onshore and offshore, including imports
- Solar photovoltaics (PV): Using existing buildings as well as the Alpine region
- Electricity from biomass: Woody and non-woody
- Deep geothermal power: Well depths > 400 m and underground temperatures > 120 °C
- Wave and tidal power: generation at the Southern European and French Atlantic coast with subsequent transmission to Switzerland
- Solar thermal power (concentrated solar power or CSP): Electricity from CSP plants in the Mediterranean area could be imported to Switzerland
- Nuclear power: Construction of new nuclear power plants based on existing technology in

Switzerland is no longer allowed, since the Swiss population agreed to the energy strategy 2050 on May 25, 2017
- Natural gas and coal power: Large, centralized combined cycle (CC) power plants, and relatively small, decentralized combined heat and power (CHP) units are considered for natural gas. Hard coal and lignite power plants are considered as options for electricity imports
- Fuel cells (FC): Different types of fuel cells operating with natural gas and biomethane as fuels and acting as combined heat and power (CHP) generation units are considered

Novel technologies have been considered but are not presented here, including hydrothermal methanation of wet biomass (PSI's catalytic supercritical water process), novel geothermal technologies, nuclear fusion, and thermoelectrics for stationary waste heat recovery.

System aspects, i.e., the interaction of different power generation technologies, the availability of different storage technologies, and the necessary expansion of the transmission grid as part of the overall electricity supply system, are beyond the scope of this work and have not been addressed. Similarly, analysis of external costs (e.g., health impacts due to air pollution or costs resulting from consequences of accidents not covered by insurance) has been excluded. However, PSI's Laboratory for Energy Systems Analysis (LEA) has carried out extensive research taking a holistic nexus perspective for a better understanding of the interdependencies across sustainability, energy security and resilience domains (Gasser et al., 2019; Hirschberg and Burgherr, 2015; Hirschberg et al., 2016; Burgherr and Hirschberg, 2014).

The structure of this report is as follows. Chapter 2 provides a comparative overview of current and future potentials, generation costs and environmental burdens of domestic power generation. Chapter 3 presents deep-dives for selected technologies, namely solar photovoltaic for the whole of Switzerland and specifically for the Alpine region, biomass, hydropower, and enhanced geothermal systems. Finally, Chapter 4 addresses challenges and opportunities, and Chapter 5 highlights the main conclusions and recommendations.

1.2 Potentials for Electricity Generation

A central goal of this work was the quantification of "technical potentials" for current and future (2050) electricity generation in Switzerland, as well as potential imports from offshore wind, concentrated solar power, ocean energy, and possibly natural gas and coal power plants. However, technical potentials alone are of limited use and often ambiguous. Therefore, practical constraints in addition to technical limitations are considered, allowing determination of "exploitable potentials" for domestic electricity generation and electricity imports. These potentials are predominantly based on estimates from the literature, expert consultations and own judgements. The specification of "exploitable potentials" is based on the terminology used by the Swiss Federal Office of Energy, distinguishing between different potentials for electricity generation:

- "Theoretical potential": Refers to the physically available energy within certain geographical boundaries (e.g., within Switzerland) without any further limitations.
- "Technical potential": Refers to the share of the theoretical potential that can be used considering technical limitations. Due to potential technology developments, this technical potential might change over time.
- "Ecological potential": Fraction of the technical potential that does not cause any permanent, irreversible harm to the environment; i.e., environmental constraints are considered.
- "Economic potential" and "extended economic potential": Fractions of technical potentials that can be economically used; i.e., economic constraints are taken into account. While the economic potential can be interpreted as a business perspective without any subsidies, the extended economic potential includes incentives and subsidies such as feed-in tariffs for renewable electricity generation and can be interpreted as a national economy perspective.
- "Exploitable potential": This potential is defined as the overlap of the ecological and extended economic potential; i.e., the technical potential reduced by environmental and economic constraints. However, social concerns are not taken into account as limiting factors.

These terms can only be used and applied within this work in a partially consistent way. Furthermore, available literature is often ambiguous and does not quantify technical, but rather "expected potentials" (or somewhat limited technical potentials) without explicitly addressing limiting environmental, economic and social factors. In such cases, expected potentials are provided as they are considered as most relevant for the Swiss boundary conditions.

1.3 Electricity Generation Costs

The purpose of the economic analysis is to analyze the internal generation costs of the different technologies, based upon the trajectory of costs and generation over the lifetime of each unit. It has the goal of analyzing each technology with a common methodology, and using a common framework of shared data assumptions. As far as possible, the economic analysis also has the goal of applying a consistent level of moderate optimism to expected technological learning and advances based on the current maturity of technologies. The levelized cost methodology (also called "Life Cycle Costing", LCC) uses financial discounting to bring all construction costs forward, and all future costs backward, to the date of the plant's start of operation (Figure 1). A uniform discount rate of 5 % has been used to quantify the LCOE of all technologies, without any risk adjustment. Future costs include operating costs (fuel, and fixed and variable operation and maintenance costs), as well as end-of-life costs for plant dismantling, site restoration and waste treatment and storage costs. The net present value is amortized over the generation lifetime of the plant. The annualized cost is then divided by the expected annual generation, based on an expected capacity factor or dispatch simulation. Both current and future LCOE are quantified.

1.4 Environmental Aspects: Burdens and Potential Impacts

This work evaluates environmental burdens and potential impacts caused by the different electricity generation technologies to be used for Swiss electricity supply. The evaluation is primarily based on Life Cycle Assessment (LCA). LCA provides a comprehensive perspective taking into account the complete life cycle of products and services. In the case of energy services such as power generation, all parts of the so-called "energy chains" are included, i.e. fuel supply, infrastructure, manufacturing, power plant operation and end-of-life (EOL). This includes extraction of energy and material resources, land use, material and energy conversion, transport services as well as disposal and recycling. LCA considers emissions of potentially harmful substances into air, water bodies and soil as well as land transformation and occupation and resource depletion. So-called "direct" emissions and other burdens are caused by the operation of the generation units (power plants and CHP units), while "indirect" emissions and other burdens are caused by other processes in the energy chain (e.g., fuel supply) as well as consumption of fuels, electricity, materials and transport services for all processes within the energy chain (so-called "background processes" from a background LCA database like ecoinvent (Wernet et al., 2016)). The results represent Swiss-specific boundary conditions in the sense that – as long as data are available – parameters and technology characteristics with high impact on the environmental technology performance reflect Swiss-specific energy chains. This includes, for example, annual yields of photovoltaic and wind power plants, the origin of natural gas imports as well as subsurface geology relevant for geothermal power generation. Potential impacts on climate change – measured in terms of life-cycle Greenhouse Gas (GHG) emissions – are at the center of national and international energy and environmental policy. These GHG emissions are therefore the burden most frequently addressed by LCA studies and literature provides the most reliable LCA results concerning this issue. Potential ranges and variations in technology-specific results can therefore most consistently be addressed. Generally, life-cycle GHG emissions correlate well with many other environmental indicators representing impacts on human health and ecosystem quality such as particulate matter formation, acidification and eutrophication, ozone depletion and formation, etc. Therefore, potential impacts on climate change are used as the key environmental indicator in this study. In addition, and depending on availability of data, selected additional environmental indicators are quantified for most of the technologies. The environmental evaluation of current technologies predominantly uses existing LCA with the ecoinvent database (ecoinvent, 2016) as the most reliable and consistent source of LCIA results. In addition, new LCA has been performed for a few technologies with previously insufficient LCA data. The evaluation of future technologies is mainly based on previous LCA by PSI authors, extrapolations from current technologies considering expected future technology development and some additional external literature.

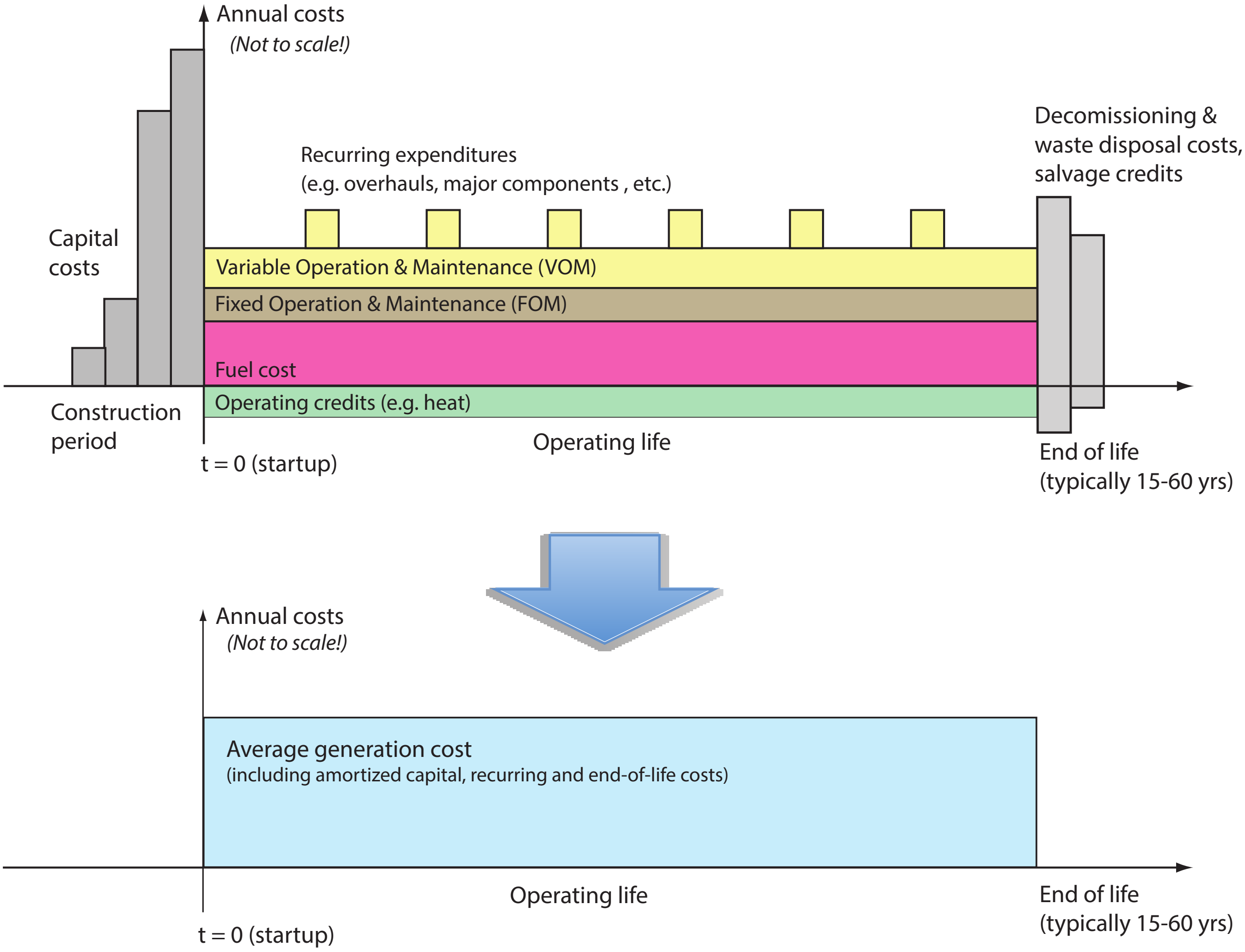

Figure 1: *Schematic diagram of LCC methodology, resulting in average generation costs per kWh of electricity, or "Levelized Cost of Electricity (LCOE)".*

2 Comparative Results

The expansion of renewable electricity production in Switzerland is the key to achieving ambitious climate targets. Photovoltaic installations, wind and hydroelectric power plants, biomass and geothermal energy have one thing in common: they should be used to the extent possible and as effectively as possible. However, there are major differences in terms of their potentials, costs and environmental impacts.

This section provides a comparative overview of current and future technology-specific electricity generation potentials in Switzerland as well as the associated power generation costs and life-cycle greenhouse gas (GHG) emissions. The main technologies that will potentially contribute to Swiss electricity supply are included in this overview: hydropower reservoir and run-of-river plants, solar photovoltaic modules, wind turbines, deep geothermal power plants, biomass conversion technologies, natural gas-fuelled, small-scale combined heat and power (CHP) plants and fuel cells as well as large-scale combined cycle power plants (with optional CO_2 capture).

Figure 2 shows the annual "exploitable" electricity generation potentials and costs in Switzerland, estimated for the year 2050 and their associated life-cycle GHG emissions. The colored bubble sizes represent somewhat optimistic estimates for exploitable potentials. Generation costs and GHG emissions represent average estimates in terms of technical performance and the size categories of installed units. Uncertainties and potential variations will be discussed in sections 3.1–3.5.

2.1 Potentials

Photovoltaic (PV) power generation exhibits by far the largest potential among renewables in Switzerland. However, its uncertainties and variations in the estimates from different sources are the largest too. It is also hard to foresee whether only buildings will be used for the installation of PV modules, which would result in a spatial correlation between population density and PV generation, or whether installations in areas with low population densities such as alpine areas will generate substantial amounts of electricity as well. The latter would be beneficial in terms of absolute yields due to higher average annual irradiation and could shift peak generation to some extent from summer to winter without reducing the annual total production, leading to a better correlation between PV generation and typical electricity demand in the mid latitudes (Kahl et al., 2019). Estimates for roof-top PV generation on existing buildings vary between about 17 TWh/a and slightly more than 50 TWh/a (Assouline, 2019; Assouline et al., 2017; Bauer et al., 2017; Swiss Federal Office of Energy, 2018; Walch et al., 2020). The reasons for this large variation are manifold: The largest differences are caused by different sources of solar irradiation data, the quantification of shading effects on rooftops, and the ways that the available and suitable roof area for PV panel installation was estimated (Walch et al., 2019). Some estimates also consider future PV technology performance, while others do not.

Generation potentials of all other renewable sources in Switzerland are at least one order of magnitude below that of PV. The estimated potential for deep geothermal power generation of 4–5 TWh/a in 2050 represents a goal established within the Swiss Energy Perspectives 2050 rather than an actual potential (Energie Schweiz, 2017). To achieve this goal, geothermal plants must reach their capacity and cost goals and must not compromise their acceptance by issues such as induced seismic events (Hirschberg et al., 2015). The potential for domestic wind power of 4.3 TWh/a in 2050 is in the same range and also a goal established within the Swiss Energy Perspectives 2050 (ARE, 2017). Considering frequent public opposition to new wind turbines (Wüstenhagen et al., 2017), it remains unclear how this goal will be achieved. One

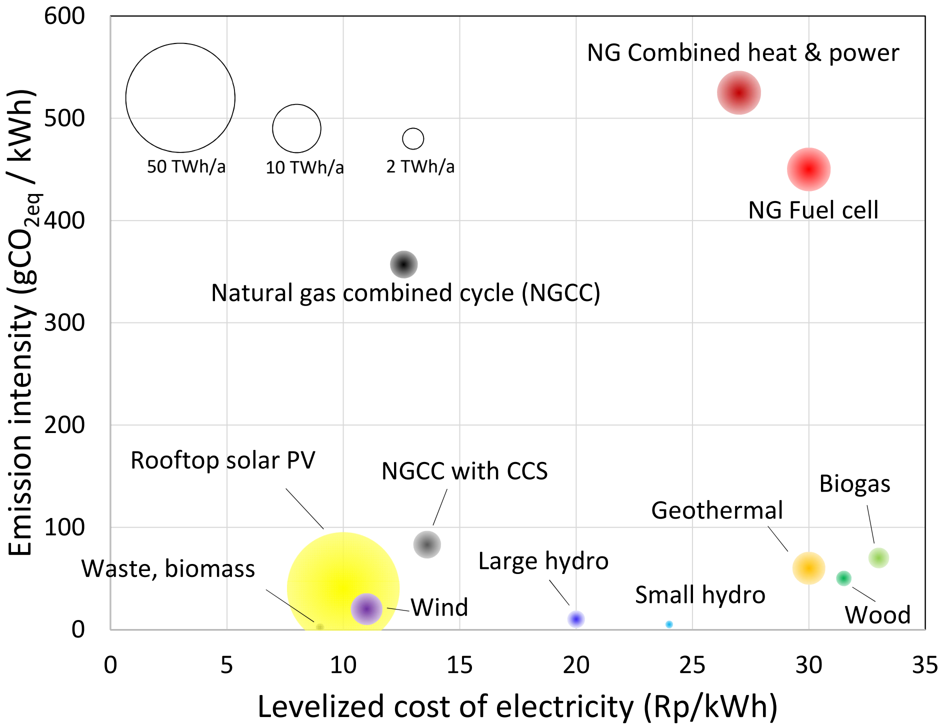

Figure 2: *Potentials and costs of electricity generation in Switzerland, estimated for the year 2050, and associated life-cycle greenhouse gas emissions. Data sources: Bauer et al. (2017), Bauer et al. (2019), and Swiss Federal Office of Energy (2012), own estimations. Bubble sizes represent annual "exploitable" generation potentials.*

option might be installations at more remote sites (at high elevation), which are often associated with the side benefits of increased overall yields and increased relative production in winter (Kruyt et al., 2017). Available biomass potentials have recently been evaluated by Burg et al. (2018): the most important biomass types for energetic use are forest wood and manure from agriculture. Conversion of biomass to electricity could generate about 3.1 TWh/a in addition to today's output (Bauer et al., 2017). Expansion potential for Swiss hydropower is limited and production is also expected to decrease due to new regulations regarding residual water flows. The additional generation potential of small hydropower plants (< 10 MW_{el}) is only on the order of a few hundred GWh/a in the best case. Expansion of large hydropower, considering reduced production due to new regulations, is estimated to generate about a further 1.2 TWh/a beyond current production (Swiss Federal Office of Energy, 2019c). However, there is considerable uncertainty related to the expected loss of production due to new regulation – according to Pfammatter and Wicki (2018), production losses could be much larger than currently estimated by the Swiss Federal Office of Energy (2019c). In addition, new hydropower plants in areas affected by glacier retreat could generate 1.6–1.8 TWh/a (Ehrbar et al., 2019). Increasing the height of existing dams of reservoir plants would not increase overall annual production, but would allow shifting 2.2–2.9 TWh/a from summer to winter (Felix et al., 2020).

2.2 Costs

Electricity generation costs (i.e., Levelized Costs of Electricity, LCOE) are an important indicator of the economic competitiveness of individual generation technologies. While current LCOE can be readily quantified, future costs in 2050 are associated with large uncertainties in future technology and fuel prices, interest rates and technology performance, among other factors. The impacts of such uncertainties can be quantified using sensitivity analysis. For certain technologies such as fuel cells, CHPs, and PV plants, a substantial economy of scale can be observed – i.e. the LCOE decreases with increasing unit capacity. Figure 3 shows an overview of current and future LCOE for electricity generation in Switzerland. Ranges shown represent the expected variability in technology performance, investment and operating costs, installed capacities, site-specific aspects and uncertainties in expected developments until 2050.

The technologies with the lowest LCOE today are biomass waste treatment, hydropower at the most economic sites, natural gas combined-cycle plants, and large-scale PV installations. Small-scale natural gas-fuelled CHPs and fuel cells exhibit the highest LCOE by far today. The most substantial cost reductions by 2050 can be expected for photovoltaics, but wind power is also expected to become cost-competitive. The LCOE of NGCC plants, CHPs and fuel cells also depend on expected fuel prices to a large extent – natural gas prices are assumed to increase by about 50 % by 2050, based on the World Energy Outlook 2018 (IEA, 2018). Also, biomass resource prices are expected to increase, which will compensate for reduced technology costs – as a result, the LCOE of electricity from biomass is expected to remain relatively stable.

2.3 Environmental Aspects

Climate change can be considered as the most crucial global environmental concern today. Electricity and heat production are the sectors with the largest share of global GHG emissions (Ritchie and Roser, 2017) by far. Hence, greenhouse gas emissions of electricity production represent a key indicator of the environmental performance of generation technologies. These emissions must be quantified from a life-cycle perspective to include not only the direct operating emissions, but also the indirect emissions associated with infrastructure production, fuel, energy and material supply chains. Figure 4 shows the life-cycle GHG emissions for electricity production in Switzerland today and in 2050. The ranges provided are due to variabilities in technology performance, unit sizes, site-specific aspects, and uncertainties regarding future developments.

Emissions from renewables are in general at least one order of magnitude smaller than those from natural gas-fuelled technologies (without CO_2 capture). The large ranges for CHPs and fuel cells are mostly related to unit capacity: smaller units are less efficient and therefore generate higher emissions. Among renewables, hydro and wind power exhibit the lowest emissions and can almost be considered "CO_2-free". PV emissions today seem relatively high, but can be expected to decrease in the future due to more efficient production processes using more renewable energy inputs, as well as improved technology performance. Variability of biomass conversion technologies is comparatively high – emissions depend on the biomass feedstock used, technology performance, and system design. Implementation of CO_2 capture at natural gas combined cycle plants could reduce life-cycle GHG emissions substantially and would result in an emission performance similar to biomass-based and geothermal electricity generation.

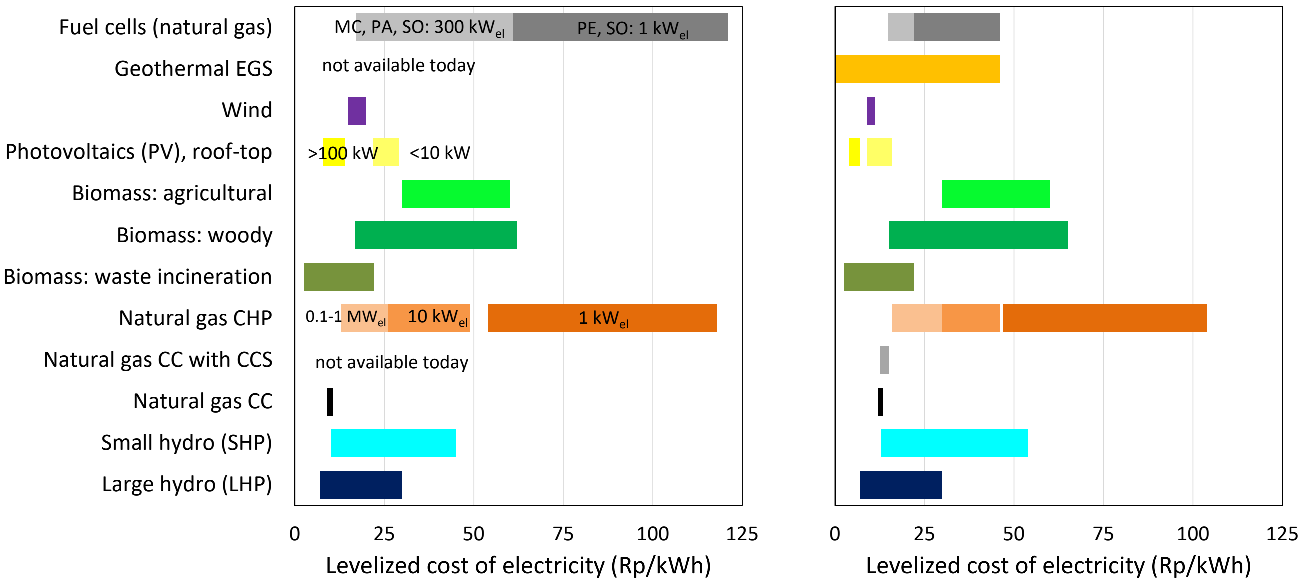

Figure 3: *Ranges of LCOE of domestic electricity generation technologies today (left) and 2050 (right). Data sources: Bauer et al. (2019) and own estimations. Current figures represent power plants (hypothetically) built today. CC: combined cycle; CHP: combined heat and power; MWI: municipal waste incineration; EGS: enhanced geothermal systems; MC: molten carbonate; SO: solid oxide; PE: polymer electrolyte; PA: phosphoric acid.*

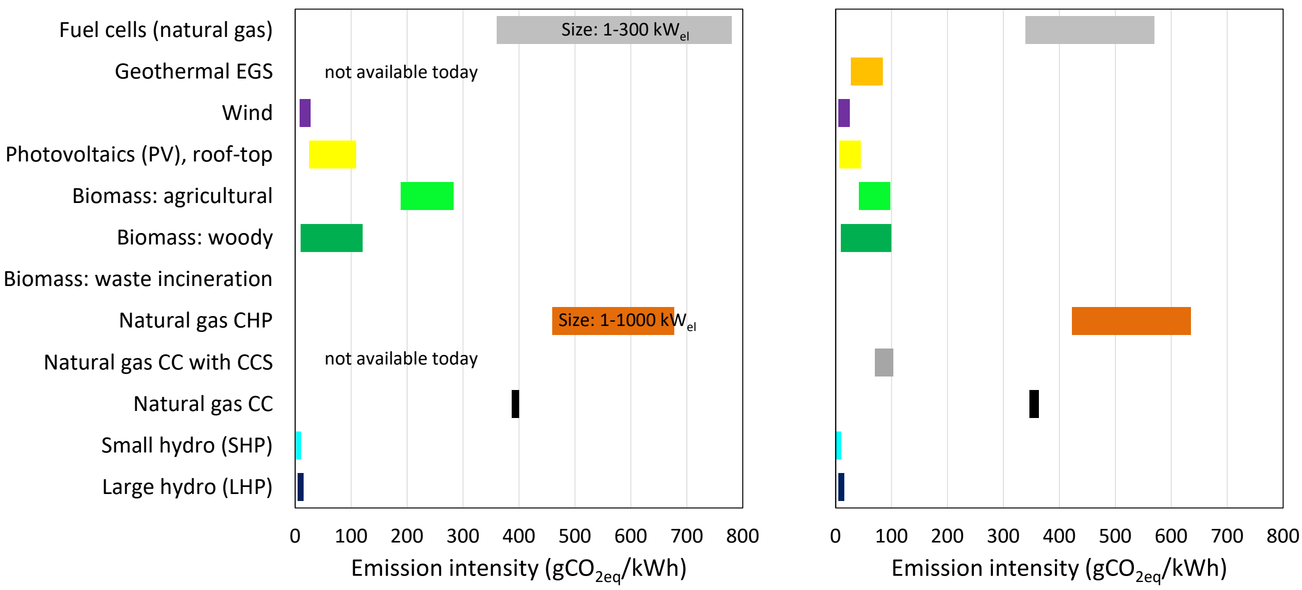

Figure 4: *Ranges of life-cycle greenhouse gas emissions of electricity generation in Switzerland today (left) and 2050 (right). Data sources: Bauer et al. (2017) and ecoinvent (2020), own estimations. EGS: Enhanced Geothermal System; PV: photovoltaic; CHP: Combined Heat and Power; CC: Combined Cycle. Further environmental life-cycle burdens have been analyzed in Bauer et al. (2019).*

3 Deep-Dives for Selected Technologies

Deep geothermal energy, biomass, hydropower and photovoltaics – due to their specific characteristics, these power generation options can very well complement each other. While photovoltaic generation exhibits distinct peaks at noon and in summer, and geothermal energy can be harvested as base-load power, biomass and hydropower offer some flexibility to match production with demand. Moreover, photovoltaic peaks can be smoothed out by smart installations in alpine areas to some extent.

3.1 Building-attached Photovoltaics

By Xiaojin Zhang

Renewable electricity produced from solar photovoltaics (PV) plays an important role in the current global energy transition. By the end of 2019, a total of 620 GW_p of solar PV systems were installed worldwide, with an annual installed capacity of 115 GW_p – an increase of 12 % compared to 2018 (IEA, 2019). Reviewing some of the major projected scenarios published in 2014 and 2015, the path that the world is currently on in terms of global cumulative installed PV capacity is among the most optimistic projections then made (Figure 5).

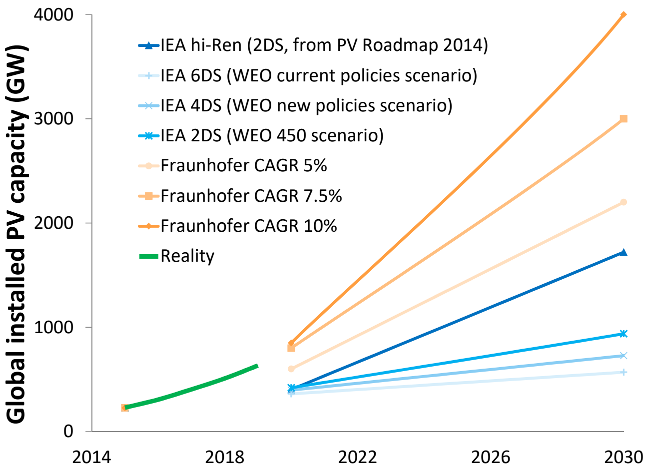

Figure 5: *Global cumulated PV installed capacity: reality (Statista, 2020) vs. projections by scenarios from 2014/2015 (Bauer et al., 2017).*

The installation of solar PV systems has grown rapidly and it currently generates about 3 % of global electricity (IEA, 2019), while in some countries, such as Germany, this share was already 8 % in 2019 (Wirth, 2020). Meanwhile, the cost has dropped rapidly in the last decade due to the learning curve effect. According to a recent report from the International Renewable Energy Agency (IRENA), an 82 % reduction in the global average levelized cost of electricity (LCOE) has been observed for electricity produced from utility-scale solar PV systems between 2010 and 2019 (IRENA, 2020).

A strong growth has been observed in Switzerland in the past 10 years. In 2019, 2.5 GW_p of installed PV systems generated 2.2 TWh of electricity (Figure 6), which corresponds to 4 % of the current national electricity consumption (Swiss Federal Office of Energy, 2019b), with an average of 870 kWh electricity generated per kW_p per year.

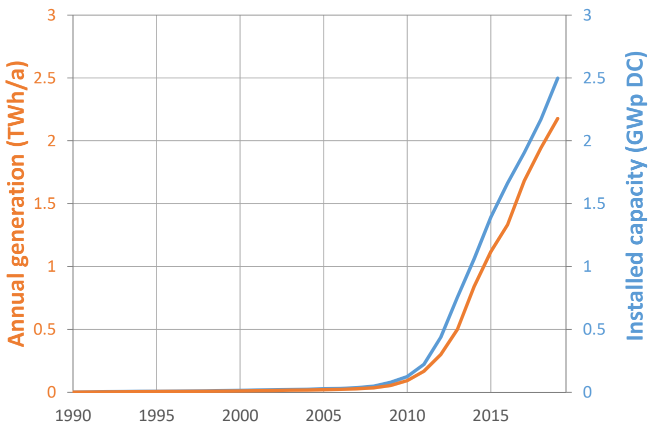

Figure 6: *Cumulated installed capacity and annual electricity generation of solar PV systems in Switzerland, 1990–2019 (Kaufmann, 2020).*

Solar PV is expected to play a key role in the national energy transition. In the Swiss energy perspectives published in 2013, it was expected to supply 6 to 11 TWh/a of electricity by 2050, depending on the selected scenario (Swiss Federal Office of Energy, 2013a). In the latest update of the energy perspectives, a more ambitious goal of reaching climate neutrality by 2050 is set, hence the projected amount of electricity generation from solar PV has increased to 34 TWh/a, which corresponds to 40 % of the current total national electricity production (Swiss Federal Office of Energy, 2020b).

Annual Generation Potential

The annual generation potential from solar PV has been analyzed by various parties. Using data from Sonnendach, the Swiss Federal Office of Energy estimated up to 50 TWh/a of electricity generation from building-attached PV systems (BAPV), and 17 TWh/a from building-integrated solar PV systems (BIPV) (Swiss Federal Office of Energy, 2019a). However, these potentials are rather theoretical. When factors such as temporal variation of solar irradiation, roof geometry and superstructures as well as the correlation between PV module efficiency and temperature are considered, BAPV systems are estimated to generate up to 24 (+/- 9) TWh/a according to another recent study (Walch et al., 2020). When solar PV generation reaches such high levels, limitations on grid infrastructure and storage can be other factors that must be taken into account to provide a realistic potential estimate. Another recent study has considered some of these aspects and arrived at an estimate of 33 TWh/a (Gupta et al., 2021).

Current and future costs

When considering the costs of solar PV, a common perception is the dramatic drop of costs in recent years, which is often associated with the low price of electricity (e.g., 4–6 Eurocents/kWh) for grid-connected MW-scale plants with power purchase agreements (PPA) in countries such as Germany (Wirth, 2020). In the US, 40 % of utility-scale solar PV systems have already reached lower costs than the cheapest fossil fuel alternatives (IRENA, 2020). In Germany, there have been unsubsidized PV projects based on PPA (Diermann, 2020) and similar trends have been observed in China. However, compared to these countries, where PV systems of more than 1 MW_p play a major role in driving the growth (EIA, 2019), only 43 % of the installed capacity in Switzerland in 2019 was contributed by systems of more than 100 kW_p (Hostettler, 2019), whereas in Germany this share was 51 %, with possibly a much higher share for systems of more than 500 kW_p (Figure 7).

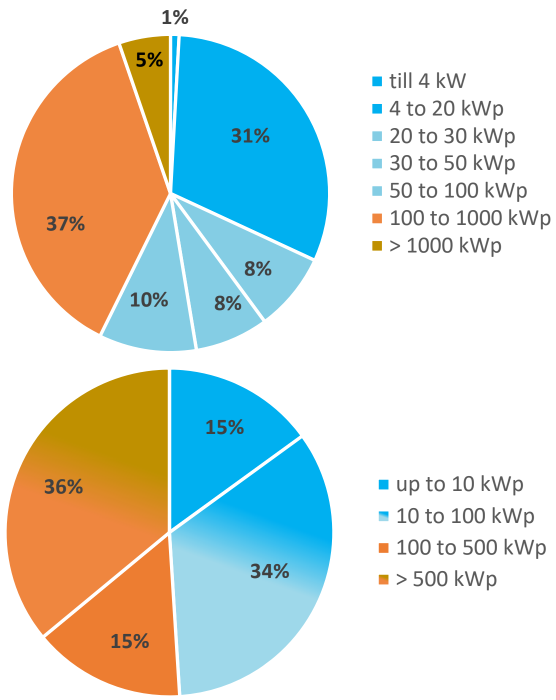

Figure 7: *Share of installed capacity by system size. Top: Switzerland (Hostettler, 2019); bottom: Germany in 2019 (Wirth, 2020).*

By number, systems of more than 100 kW_p are only 3 % of all those installed in Switzerland, while systems of 4 to 30 kW_p are 89 % (Hostettler, 2019). This indicates that 43 % of the installed capacity is contributed by a very limited number of large-scale systems, and the growth in numbers of solar PV systems in Switzerland has been dominated by small-scale applications on single family houses, which usually have an installed capacity of less than 10 kW_p (Wirth, 2020). Since the size of a PV system is closely related to its investment cost (Wirth, 2020), it is crucial to differentiate the PV cost development in Switzerland from other countries.

Figure 8 shows system investment costs by size range, based on offers submitted to Energie Schweiz from 2015 to 2021 (until Jan 2021; whenever 2021 is referred to hereafter, it refers to data in Jan 2021 only). For systems of less than 20 kW_p, a clear decrease of median costs can be observed from 2015 to 2020, while the higher range of costs

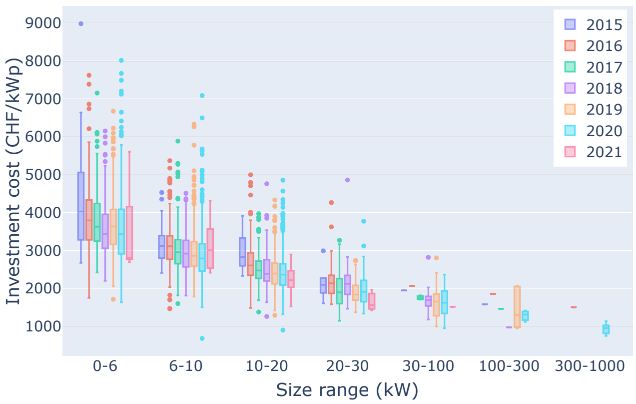

Figure 8: *Distribution box plot for selected BAPV system investment costs by system size in Switzerland from 2015 to 2021 (note that the year 2021 only contains data from Jan 2021, while the other years contain data for the entire year) (Energie Schweiz, 2021).*

for systems less than 10 kWp has increased a bit in 2020 (and 2021), likely due to the impact of shortage in material supply due to the pandemic. The decreasing trend is less obvious for systems of larger size. It also shows that the smaller the system size is, the more pronounced the cost decrease is throughout the years. Interestingly, more outliers can be seen in more recent years than previously for system size from 6 to 10 kW_p (a common range of system size that is installed in single family houses). Since the data sampled from these offers are mostly for small-scale systems of less than 100 kW_p, system investment costs used in this analysis for larger systems are based on expert judgements (Table 1).

In comparison with the system investment costs for small-scale rooftop PV systems (i.e., systems up to 10 kW_p) in Germany of about 1600 to 1850 EUR/kW_p in 2019 to 2020 (Hannen, 2019; Solaranlagen Portal, 2020), the median system investment costs in Switzerland from 2020 to 2021 (about 3100 CHF/kW_p) are around 63 % higher. The minimum system investment costs in both countries are on a comparable level of around 1500–1630 CHF/kW_p. The investment cost for systems from 10 to 100 kW_p is around 1950 CHF/kW_p in Switzerland from 2020 to 2021, which is about double the average investment cost for PV systems in Germany of the same size in 2019, of about 1050 EUR/kW_p (Philipps and Warmuth, 2020). Capital investment cost for systems from 300 kW_p to 1 MW_p is around 960 CHF/kWp in Switzerland from 2020 to 2021 (Energie Schweiz, 2021). For systems from 10 to 100 kW_p, PV modules are 45 % of the system investment cost in Germany (Wirth, 2020), while this is slightly less than 30 % in Switzerland.

In general, the system investment costs for small-scale PV systems in Switzerland remain high in comparison with Germany. The cost breakdown by component (Table 2) shows that the costs for Module and Other, balance-of-system (BOS) costs in Switzerland are higher, but the latter contribute more to the cost difference, which may be due to higher profit margins, administrative and labor costs in Switzerland. To facilitate further deployment of PV systems in the future, it is worthwhile to systematically look at the causes of these higher costs and to formulate a corresponding policy to reduce them.

Annual O&M costs have further decreased according to a study in 2018 (Toggweiler, 2018), to 3 Rp./kWh of electricity produced for systems of less than 100 kW_p, and 2 Rp./kWh for systems above 1 MW_p, including the replacement of both inverters and BOS components. This, decommissioning costs and other key assumptions for the calculation of current LCOE in Switzerland are summarized below, as well as in Table 1 and Table 2.

- Annual O&M cost (Bauer et al., 2019); based on Toggweiler (2018), including replacement cost:
  - Small systems ($\leq$100 kWp): 3 Rp/kWh
  - Large systems ($>$100 kWp): 2 Rp/kWh
- Decommissioning costs (Bauer et al., 2017; Philipps and Warmuth, 2020):
  - Labor: labor cost is 50 % of system capital cost
  - Cost for disposal is assumed to be equal to the residual value of the entire system, i.e. the waste value of the system at end-of-life is sufficient to finance its decommissioning
- Other key assumptions (Bauer et al., 2019):
  - Annual average yield: 1013 kWh/kW_p (Vontobel et al., 2016)
  - Performance ratio: 80 % (Vontobel et al., 2016)
  - Area required per kW_p installation: 6 m^2/kW_p
  - Average module efficiency: 17 % (Philipps and Warmuth, 2020) (Although according to Wirth (2020), the efficiency of new silicon-based PV modules today is about 20 %, to be consistent with the assumption used in Walch et al. (2020), which is referred in the analysis for Figure 10, the module efficiency is assumed to be 17 %.)
  - Average annual solar irradiance: in order to match the yield above: 1267 kWh/m^2/year of annual solar irradiance must be assumed (reference: Mittelland: 1100 kWh/m^2/year; Swiss Alps: 1400-1600 kWh/m2/year)
  - Annual electricity production degradation rate: 0.5 %
  - Average inverter efficiency: 98 %
  - Lifetime: 30 years
  - Interest rate: 5 % & 2 %

Table 1: *Current PV system investment costs (systems up to 100 kWp: median system capital costs provided by SFOE in Jan 2021 (Energie Schweiz, 2021), as shown in Figure 8; systems more than 100 kWp are based on Sauter and Jacqmin (2020)).*

Size (kW_p)	**0–6**	**6–10**	**10–20**	**20–30**	**30–100**	**100–300**	**300–1000**	**>1000**
Investment costs (CHF/kW_p)	3430	2790	2360	1910	1590	1283	1060	780

Table 2: *Breakdown of current system investment cost (Sauter and Jacqmin, 2020).*

Size (kW_p)	**0–10**	**20–30**	**30–100**	**100–300**	**>300**
Module	19 %	25 %	30 %	32 %	34 %
Inverter	11 %	9 %	8 %	8 %	9 %
BOS (structure)	10 %	12 %	12 %	10 %	8 %
Administration, planning, etc.	17 %	14 %	11 %	13 %	11 %
Other	43 %	40 %	39 %	36 %	38 %

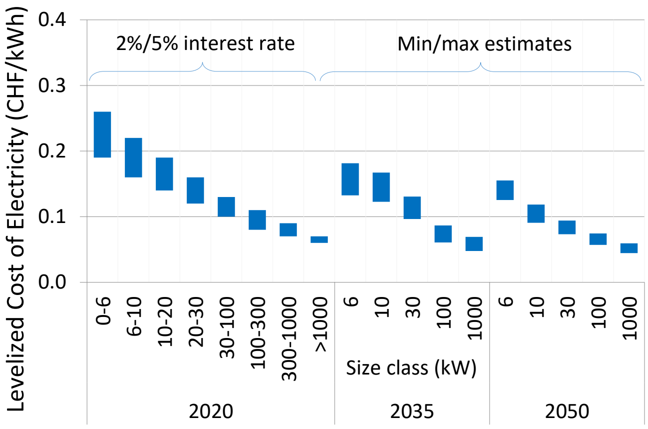

Figure 9: *Range of current and future LCOE for electricity generated from BAPV systems in Switzerland. Current LCOE are calculated based on the median system investment costs in Table 1. Future LCOE in 2035 and 2050 are based on Bauer et al. (2017)*

The LCOE for BAPV systems by size is shown in Figure 9. Since the interest rate for PV systems – especially for small systems, e.g., on single family houses – might be lower than that used for other power generation technologies (5 % is used as baseline for all other electricity generation technologies in this synthesis report), results are provided here for interest rates of both 5 % and 2 %. The LCOE ranges from 7–26 Rp/kWh with interest of 5 %, or 6–19 Rp/kWh with interest of 2 %.

Given the remuneration of mostly less than 10 Rp./kWh when PV generation is fed into the grid (VESE, 2020), as well as the grid electricity price of mostly more than 15 Rp./kWh (e.g., for single family houses with about 7500 kWh of annual electricity consumption (ElCom, 2020a), two conclusions can be drawn for small-scale applications (i.e. less than 10 kWp): first, the LCOE for PV is still likely more expensive than the grid supply (tax reductions have not been taken into account because sustainable long-term rollout of PV needs to be subsidy-free); second, self-consumption should be highly encouraged, as it is economically more beneficial to meet the owner's electricity demand with onsite renewable generation from the PV systems, avoiding grid supply rather than selling it back to the grid.

Future LCOEs for BAPV systems projected in 2017 are shown in Figure 9 (Bauer et al., 2017), based on reduced costs due to learning or efficiency improvements. It shows that in 2050, depending on the system size, LCOE could reach 4–16 Rp./kWh, which is cost competitive given the current standard electricity tariff of 12–24 Rp./kWh for commercial and industrial customers, and 17–28 Rp./kWh for households in Switzerland, as well as the likely increasing electricity prices in the future (Panos and Densing, 2019). A closer investigation of the driving factors for future LCOE reduction shows the essential role of module price for all system sizes, despite its steadily decreasing relative contribution to the overall system capital cost (Bauer et al., 2017).

Annual electricity production potential vs. levelized cost of electricity (LCOE)

Based on data for each individual rooftop in Switzerland and the new estimates of PV module costs, efficiencies and other parameters, more realistic future LCOE and generation potentials were estimated by Bauer et al. (2019). In the previous analysis, simple estimates were based on using 100 % and 70 % of available rooftop area, taking into account the potential reduction due to obstacle roof areas. The approach applied is thus subject to high uncertainties, as potential competing uses of rooftops (e.g., solar thermal heat collectors, chimneys, etc.) are not taken into account. A recent new study published by Walch et al. (2020), addresses some of these limitations, so the analysis carried out in Bauer et al. (2019) has been improved by using more realistic estimates of available area and annual electricity generation potential from this study.

Figure 10 shows generation potential as a function of LCOE, based on system investment costs

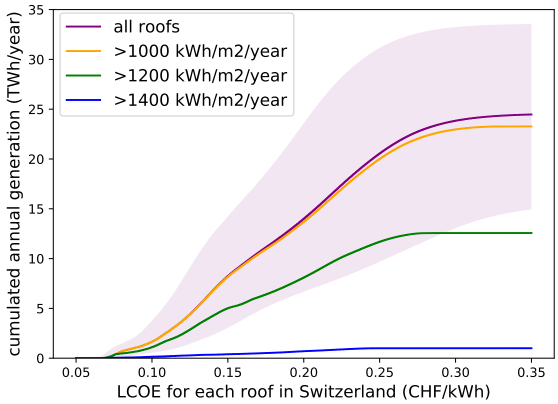

Figure 10: *Correspondence between annual electricity generation potential (Walch et al., 2020) and LCOE (lines representing considerations of roofs with different solar resources), considering uncertainties of annual generation potential and available area for all roofs (shaded area).*

in 2020 and January 2021 (as updated in this analysis) and improved estimates from (Walch et al., 2020).

It shows that the curve flattens when LCOE is more than 25–30 Rp./kWh, indicating that the majority of this potential could be achieved with a LCOE below this cost range. The lowest LCOE is more than 6 Rp./kWh, which is comparable to the current electricity tariff and the feed-in tariff (mostly from 6–8 Rp./kWh, with a few municipalities providing up to 12–15 Rp./kWh, and less than 6 Rp./kWh in Switzerland for PV systems with more than 10 KVA capacity (VESE, 2020). Given that electricity tariffs in Switzerland range from 17 to 25 Rp./kWh (ElCom, 2020b), it shows that self-consumption should be prioritized over feeding the grid in order to improve the economic attractiveness of the installed systems. More renewable electricity in the future will increase the demand for grid flexibility, as well as grid service charges in electricity tariffs (Panos and Densing, 2019), which has been observed in Germany in the past decade (Statista, 2020). This will make self-consumption even more attractive in the future.

Figure 10 shows that when the uncertainties in annual generation potential, area and tilted solar radiation are neglected, more than 90 % of the total generation potential comes from the roofs which have tilted solar radiation of more than 1000 kWh/m^2/year (i.e., comparing the orange and purple solid lines). The potential for roofs with more than 1400 kWh/m^2/year of tilted solar radiation is negligible, and much of this potential is already realized today. This means that the deployment of rooftop solar PV systems should not be limited only to the roofs with the best solar resources. When standard deviations for the uncertain parameters are considered, the solar radiation exhibits very high uncertainty (shaded area, Figure 10), with the higher-bound potential for all roofs matching roughly with the projection for solar PV potential of 34 TWh/year, as in the latest climate-neutral Swiss energy perspective scenario (Swiss Federal Office of Energy, 2020b).

There are also some limitations to the estimated costs shown in Figure 10. First, the estimated costs do not include any grid infrastructure investments needed to ensure stability of the overall electricity supply system, which is required when substantially higher amounts of decentralized PV systems are installed. It may not be economically viable to expand the grid capacity to accommodate all decentralized PV generation. Depending on the local constraints (e.g., economically viable power capacity additions at the voltage level of the network), it may be necessary to curtail PV generation at peak hours. In addition, any potential social concerns (e.g., local acceptance based on aesthetics) and restrictions are not considered. Addressing such aspects will require the use of energy or electricity system models capturing more systemic issues, which should be addressed in future analysis.

3.2 Alpine Photovoltaics

By Annelen Kahl & Michael Lehning

As shown in the previous Section 3.1, a large share of the future electricity generation can be supplied by photovoltaics on buildings, either added on rooftops or integrated in facades. However, that generation can easily exceed demand in summer months, but it is low in winter months when Switzerland's peak load occurs.

The important question is thus: Is it possible to shift overproduction from summer months to the cold and dark winter months with high demand? Currently, there are no real seasonal electricity storage options. Increasing the storage volume of the Swiss reservoirs can help to shift energy production from summer to winter, whereas pumped hydro storage operates on a daily to weekly pattern, and the available storage volume of a few hundred GWh

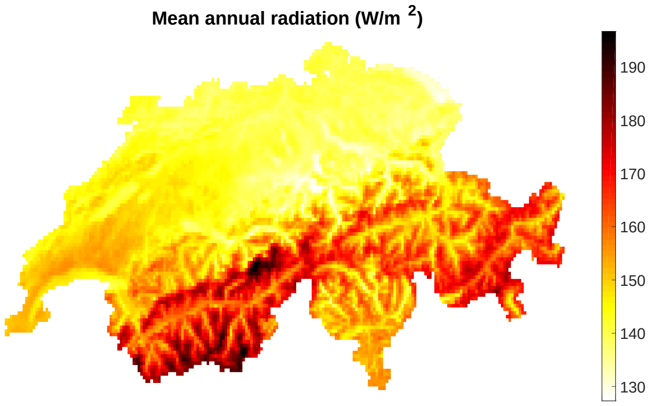

Figure 11: *Long-term average solar radiation on a country-wide grid with a spatial resolution of 1.6 km x 2.3 km.*

is insufficient for seasonal balancing.

However, if installation geometry and locations are well chosen, solar installations in the mountains can produce more electricity in winter than in summer, and total annual generation exceeds that of equally sized installations in the lowlands (Kahl et al., 2019).

The four advantages of alpine PV

There are four reasons for this production advantage at higher altitudes:

- At higher altitudes there simply is more solar radiation (see Figure 11). First, the atmosphere is thinner and therefore less solar radiation is absorbed before it reaches the module surface. And second, fog and cloud cover in winter are often limited to the lowlands, while the mountains have full solar energy at their disposal.
- Snow cover, due to its high reflectivity, increases the solar energy reflected back from the ground and thus makes an additional contribution to electricity production.
- The first two points can be further enhanced by using steep tilt angles for the solar modules. The more snow surface is "seen" by the panel, the higher the contribution of ground reflection. Furthermore, steep angles favour winter production, because the low winter sun falls more vertically on the module surface (and snow slides off the panel more easily should it start to accumulate).
- The efficiency of PV systems increases as the module temperature decreases. Typical ambient temperatures and wind speeds at high altitudes thus have a positive effect on electricity production compared to the lowlands.

City and mountain scenarios

In order to assess the benefits of alpine PV, we developed the SUNWELL model, which can explicitly calculate electricity production in space and time for all of Switzerland based on satellite-derived radiation data and module orientation. We defined three scenarios, all with a total annual production of 12 TWh. This corresponds to about half of Switzerland's current nuclear production.

Results are presented in Figure 12. In the urban scenario, PV plants with a fixed tilt of 25 degrees are installed in regions of high population density, i.e., mainly in the urban areas of the plateau (red). For the second scenario the arrangement is optimized for maximum annual production (black). The third scenario aims at maximum winter production (blue).

For alpine PV, we exclude all areas above 2500 m altitude, all slopes steeper than 30 degree including a 100 m buffer, as well as forests, protected zones and other landscape types that are not suitable for PV installations. Furthermore, we only allow installations within 500 m of existing roads, to exclude inaccessible installation locations. And finally, we limit the surface coverage of PV modules in the remaining regions to a maximum of 5 % to avoid an unrealistically high installation density.

Figure 12 (left) shows the spatial distribution of PV installations over Switzerland. The urban scenario requires 57.2 km^2 of panel surface, whereas the maximum annual and maximum winter production variants require only 44.2 and 44.7 km^2, respectively. Figure 12 (right) depicts the average annual production profiles for the three scenarios. The two variants that include alpine PV exhibit indeed a much smoother profile with less pronounced differences between summer and winter.

In order to realize the advantages of alpine PV, a number of practical problems must be solved: The installation of solar PV in mountains is more expensive and limited by landscape-protection considerations. The harsh weather conditions may require more frequent servicing and may lead to production losses due to ice or snow accumulation. These problems need to be investigated further. In addition, the construction of new roads and power lines can be expensive, particularly in alpine conditions, and may also be subject to social opposition on environmental or aesthetic grounds. The use or

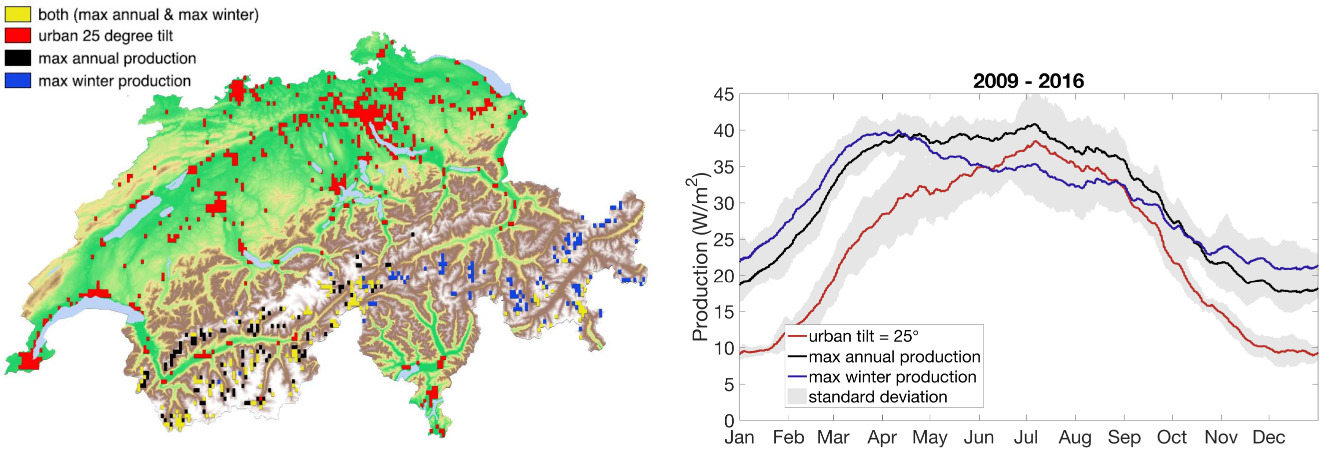

Figure 12: *Comparison of conventional production on building roofs (red) with installations of optimized site selection and module orientation for maximum annual production (black) and maximum winter production (blue): (left) Site selection map, (right) mean (line) and standard deviation (shading) of production profiles for the years 2009–2016, smoothed with a 30-day moving average.*

expansion of pre-existing infrastructure such as access roads and power lines leading to alpine dams, ski areas, buildings and even avalanche defense structures for alpine PV installations should therefore be considered as part of an important step in closing the Swiss winter electricity gap.

3.3 Biomass

By Serge Biollaz

The use of bioenergy has been a fundamental element of human and social evolution. A short retrospective shows the context of past different drivers for bioenergy use, and what might drive the use of this technology in the future.

Humans have used wood fires for cooking and heating for at least four hundred thousand years. For six thousand years, charcoal was used in metallurgical processes, first to produce copper, and then also to make bronze and iron. James Watt's steam engine of 1776 was one of the driving forces of the industrial revolution, but locally available biomass, i.e., wood, could not supply the needed demand of fuel for the steam engine. The availability of high-yield, easily accessible fossil biomass (i.e., coal deposits) was crucial for the massive expansion of steam engines and later steam turbines.

Due to the absence of significant coal deposits in Switzerland, hydraulic power was used instead of steam engines in the Swiss industrial revolution as it was relatively easily accessible. Nevertheless, the population growth and industrialization led to an overuse of Swiss forests. In order to protect the Swiss forests, the first forest law was put into place in 1876.

In the 1960s and 1970s, environmental concerns led to a controlled use of bioenergy in order to protect water, soil and air. Many waste water treatment plants (WWTP) were built at that time. The sewage sludge generated in WWTP is digested, and the biogas produced can be used for combined heat and power (CHP) production with gas engines. This mainly covers the WWTP's own electricity and heat demand.

For centuries, municipal solid waste (MSW) was landfilled. Environmental concerns and the lack of space in Switzerland finally led in 2000 to a ban on the landfill of combustible waste, including organic wastes such as waste wood and green waste from households. Since the 1970s, MSW incineration capacity has considerably increased in Switzerland. In such combined heat and power plants, steam is produced for generation via steam turbines (similar to coal combustion plants). The heat also produced at these sites is distributed via municipal district heating networks.

Over the past thirty years, other technologies were implemented into the market, such as biomass combustion, gasification and advanced biogas digestion technologies. This development was mainly triggered by economically attractive feed-in-tariffs such as the EEG (Erneuerbare-Energien-Gesetz) in Germany or the KEV (kostenorientierte Einspeisevergütung) in Switzerland.

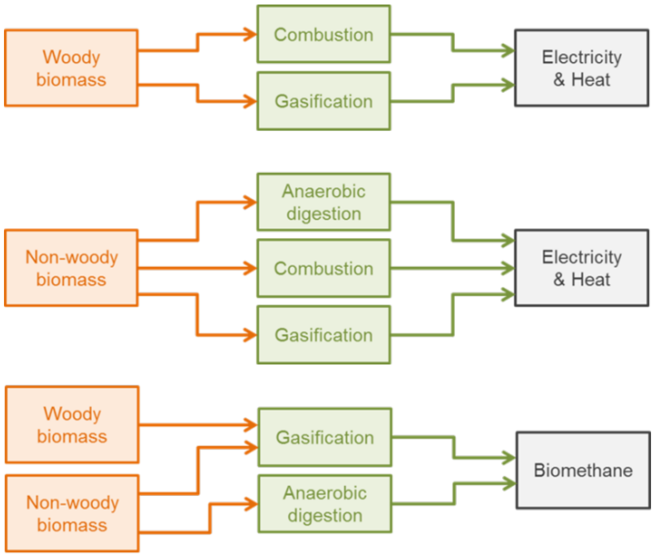

Figure 13: *Broad overview of conversion pathways from biomass resources to electricity, heat and biomethane (Bauer et al., 2017).*

Today, biomass for electricity generation encompasses a range of feedstocks, processing steps, and conversion technologies. Very broadly, electricity can be generated from biomass following the pathways shown in Figure 13.

The direct conversion pathways from biomass to electricity are shown on the left-hand side. Alternatively, biomass can also be transformed first to biomethane, which is chemically similar to natural gas and can therefore be transported through the existing natural gas grid. Biomethane can be used to generate electricity (and heat) when needed, without being tied geographically or in time to the original place of the biomass resource production.

Types of feedstock can be broadly categorised as "woody" or "non-woody" biomass. Woody biomass consists of forest wood, industrial wood residues, waste wood, and wood from landscape maintenance. These resources can be directly converted into electricity by either combustion or gasification pathways. Combustion is by use of a CHP system to directly produce electricity from the high temperature heat (i.e., steam turbines or Organic Rankine Cycles). Gasification is followed by any power production technology that can use gaseous fuel as a feedstock (e.g., internal combustion engine, turbine or fuel cells).

Non-woody biomass consists of several feedstock types with higher water content than woody biomass, including organic fractions of household waste, industrial bio-waste, agricultural crop by-products, green waste, animal manure, and sewage sludge. Feedstocks with high water content (sewage sludge, manure, etc.) are handled through an anaerobic digester. The resulting biogas can be used directly to generate electricity and heat in a gas engine, gas turbine, or fuel cell. Feedstock with lower water content can be combusted to drive a steam or organic Rankine (ORC) cycle. Gasification of waste is also technically feasible today but not so widespread as combustion/incineration of waste.

Current costs in Switzerland

Woody biomass. Case studies have been compiled for typical plant sizes in Switzerland and Europe (Bauer et al., 2017). Four different scales of installation have been considered ranging from 750 kWe up to 8 MWe, using only conventional combustion technologies. Heat is these plants' main product, i.e. 70 % of the input energy is converted into heat. The electrical efficiency is 20 % at best.

Typically, each plant must be designed based on local requirements. Based on multiple case studies, well-known interdependencies have been confirmed, including the cost of feedstock, annual operation hours, scale of installation and value of the heat sales. The resulting cost of electricity therefore varies over a considerable range (Figure 14). For clean wood, the cost ranges from 17 Rp/kWh up to 62 Rp/kWh, assuming heat sales at 8 Rp/kWh. For the same value for heat, but burning 50 % waste wood, the cost of electricity is lower (between 4 Rp/kWh to 53 Rp/kWh).

Non-woody biomass. Multiple case studies have been compiled for typical agricultural biogas plants in Switzerland as well as for Europe (Anspach and Bolli, 2015; Anspach and Bolli, 2018). These studies have helped to characterise the cost structure and quantify electricity production costs for three typical Swiss plant sizes. The first case study looked at a typical small plant with more than 95 % manure use and an average installed electrical output of 24 kWe. Second, a medium-sized biogas plant was considered with 82 % manure use, around 7000 t substrate use and an installed electrical output of 130 kWe. The third case was a typical large biogas plant with 85 % manure, around 16'000 t substrate used per year and an installed electrical output of 380 kWe.

In comparison to other renewable energy technologies, the electricity production costs of biogas plants seem to be rather high at 32–37 Rp/kWh

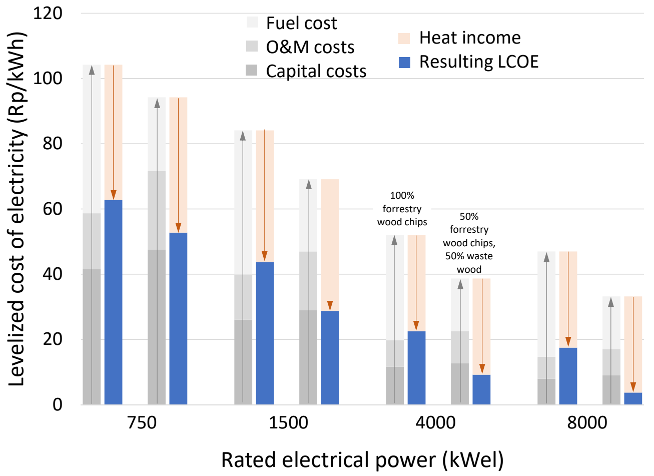

Figure 14: *Resulting Levelized Cost of Electricity for wood-based power plants.*

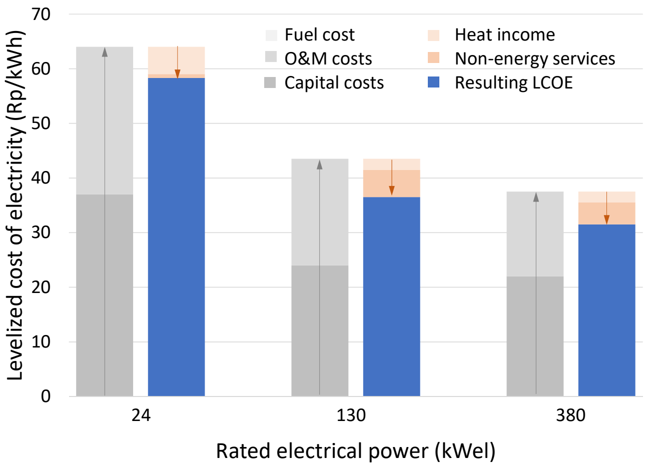

Figure 15: *Resulting Levelized Cost of Electricity for biogas based power plants.*

(Figure 15). For small plants costs are even higher. Investment and operating costs contribute similarly to the production costs. This high levelized cost of electricity (LCOE) is also due to the lack of other revenues for such biogas plants. So far, all the multiple functions and services provided by agricultural biogas plants are only paid for by the amount of electricity produced and the Swiss feed-in-tariffs.

Future costs in Switzerland

While the current range of the LCOE from biomass can be quantified, their future cost in 2050 is uncertain due to, e.g., future technologies and technology performance, feedstock cost and interest rates. Biomass feedstock prices are expected to increase, which will compensate for expected reduced technology costs. As a result, LCOEs from biomass are expected to remain approximately at the current level.

Woody biomass. There are multiple ways to produce bioelectricity from woody biomass. Most likely only CHP technologies will have a market application in 2050. This will be large-scale CHP plants based on combustion at industrial sites or small-scale clean wood gasification CHP systems with a local district heating network.

Non-woody biomass. In the future, a reduction of specific investment costs can be expected, due to the increase in size of central biogas plants to an expected electrical output of 450 kWe and the increasing standardisation of small-scale, farm-based biogas plants at 24 kWe. Operating costs will remain constant. Agricultural biogas plants will be able to reduce electricity production costs when services such as nutrient efficiency, climate protection or heat sales are compensated.

The changing role of Bioenergy

Over thousands of years, biomass has been used for all kinds of end uses. Bioenergy and specifically bioelectricity is just one option. In the near future, i.e., until 2050, new requirements for bioenergy plants are expected, mainly driven by the future need for flexible of electricity production (in time and space), the demand for high temperature heat, and the overall net zero-emission goal of Switzerland.

Therefore, it is important to develop and implement new business ideas for bioenergy, which serve the needs of the whole energy system of the future. This means for instance, that base load operation of biomass combustion CHP is only then acceptable, if the biomass must be used within a short time frame, if no seasonal storage of the bioenergy is possible, or if there is a permanent demand for high temperature heat. Such a mindset may also be required for small-scale wood CHP systems based on wood gasification or biomass digestion.

Another new role for biomass in Switzerland may also be the net capture of CO_2 from the atmosphere. There are multiple ways to store CO_2, such as in construction materials, with a sustainable carbon inventory in the soil or by producing hydrogen from biomass with carbon capture and sequestration. Biomass has an important role in the future Swiss energy system due to its flexibility and integrative role as a source of chemicals (fuel, gas, reducing agent), heat, electricity and storage. Its energy application is most likely also constrained by the possible role within the bio-economy in general, as well as in a larger strategy or policy for integrated, sustainable landscape, agriculture and forestry management.

3.4 Hydropower

By Christian Bauer & Martin Densing

Hydropower is the foundation of Swiss power generation: in 2019, hydropower plants contributed around 56 % of domestic generation (run-of-river: 24.6 %, reservoirs: 31.8 %) . Due to its comparatively low generations costs, very low life-cycle environmental burdens, and flexibility in electricity production from reservoirs, hydropower can be considered to be among the preferred generation options in Switzerland – now, and also in the future. The Swiss energy strategy and climate policy aiming at net-zero CO_2 emissions in 2050 suggest that hydropower must keep this role, even expand production, and adjust operation regimes to meet new flexibility demands resulting from the integration of larger amounts of intermittent renewable generation. However, hydropower potential is limited, new plants often face opposition, and new regulations may lead to a reduction in electricity production from existing plants.

Potential

The Swiss Federal Office of Energy (SFOE) recently published an update of the estimated hydropower electricity production potential in Switzerland, covering both large and small hydropower and new power plants as well as refurbishment of existing units (Swiss Federal Office of Energy, 2019c). The latest developments in the electricity market and the expected effects of new regulations have been taken into account. An in-depth analysis of potential new reservoir plants in the periglacial Swiss Alps, i.e., in regions that have recently or will become ice-free due to glacier retreat in the near future has been performed (Ehrbar et al., 2019). Furthermore, the option of increasing dam heights at existing reservoirs has been investigated in detail (Fuchs et al., 2019). The latest insights on hydropower generation potentials, based on these analyses, can be summarized as follows:

- Large hydropower (both new plants and refurbishment of existing plants) could increase production by about 2.9 TWh/a in a scenario with optimized boundary conditions being more favorable for hydropower exploitation than today's regulation.
- Small hydropower could – based on the same scenario – increase production by about 0.8 TWh/a, while a shut-down of some existing plants is expected to lead to a reduction of production by about 0.2 TWh/a.
- At the same time, a reduction of overall hydropower generation on the order of almost 2 TWh/a can be expected due to new regulations regarding residual water flows.
- The potential of new reservoir plants in the periglacial Swiss Alps is highly uncertain due to environmental and social concerns and the fact that many of these plants would be located in protected areas. An additional annual generation of 0.7 TWh might be expected.
- Increasing dam heights and water storage volumes would hardly increase overall annual power generation from these reservoir plants, but would allow for a shift from summer to winter generation.

In total, hydropower in Switzerland could increase its annual generation by about 2.3 TWh, if regulations could be modified to be more favorable for hydropower exploitation than today's regulation.

Costs

New cost estimates for hydropower in Switzerland are not available and therefore, the figures provided in Bauer et al. (2017) and Bauer et al. (2019) can still be considered as valid. Levelized costs of electricity from new large hydropower plants built today are estimated to be on the order of 7–30 Rp./kWh, those of electricity from small hydropower plants on the order of 10–45 Rp./kWh. Cost estimates for electricity from reservoir plants in the periglacial Swiss Alps are not available. Major changes for costs of hydropower plants to be constructed in the future cannot be expected, since hydropower represents a mature technology. It can, however, be expected that the most economic sites for new plants would be exploited first, which would result in cost increases over time for plants built in the future.

Environmental burdens

In the context of environmental concerns related to hydropower, local and regional impacts on ecosys-

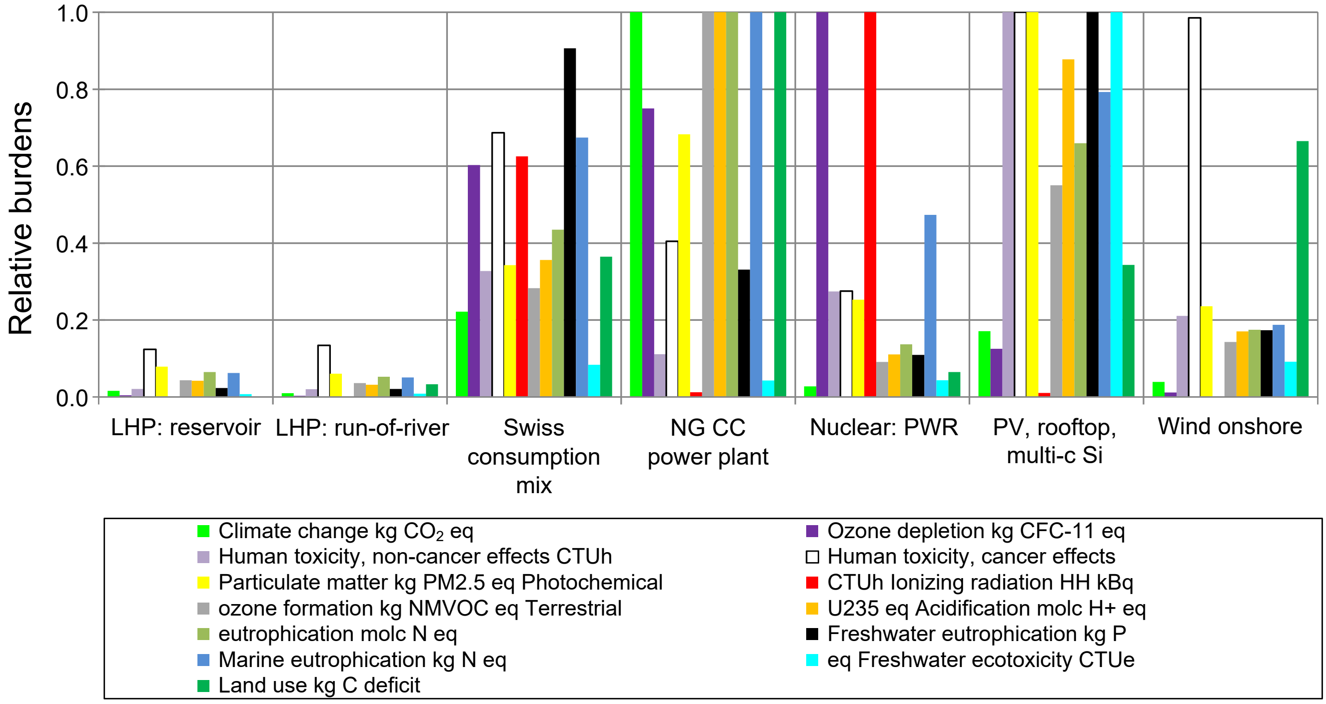

Figure 16: *Life-cycle environmental burdens of large hydropower (LHP) compared to other options in Switzerland, representing current technologies (ecoinvent, 2016). NGCC: Natural Gas Combined Cycle; PWR: Pressurized Water Reactor; PV: Photovoltaics. Burdens are normalized to the technology with the highest score in each impact category (=1).*

tems must be distinguished from life-cycle environmental burdens. Local and regional impacts must be evaluated specifically for each hydropower plant and its specific environmental boundary conditions and thus, general statements cannot be provided. The life-cycle perspective does not consider location-specific aspects; instead, it aims to quantify environmental burdens from the perspective of the overall life-cycle of power plants including burdens associated with construction, operation, and end-of-life of the power plant infrastructure. Impacts on climate change, human health, ecosystem quality and resource consumption are quantified, based on certain impact categories for each of those areas of concern. From this life-cycle perspective, hydropower is – compared to other options for electricity production – a very clean form of power generation, since the lifetimes of infrastructure elements are long and the environmental burdens associated with construction of the plants can be "amortized" over a large amount of electricity generated.

Figure 16 shows a comparison of the environmental life-cycle burdens of power generation based on recommended impact assessment methods according to (Hauschild et al., 2013). Large hydropower in Switzerland exhibits comparatively low burdens in all impact categories.

Location-specific environmental impacts on local and regional ecosystems must be considered in addition to these life-cycle burdens on a case-by-case basis.

Market profitability

Triggered by the decreasing wholesale electricity market prices in the years 2010–2016, concerns about insufficient market profitability of hydropower in Switzerland led to a series of studies (Swiss Federal Office of Energy, 2013b; Swiss Federal Departments DETEC and SFOE, 2014; Filippini and Geissmann, 2014; Piot, 2015; Schlecht and Weigt, 2016; Pöyry, 2019); although price levels stabilized partially after 2017 (Panos and Densing, 2019). Swiss hydropower is mainly a price-taker on the electricity markets, that is, Swiss capacity is relatively small compared with capacity of the surrounding countries, which significantly influence Swiss domestic wholesale prices.

Key factors determining prices, which are likely to prevail at least up to 2035, include fossil gas prices (still expected to be used for power generation in surrounding countries) and short-term variations in

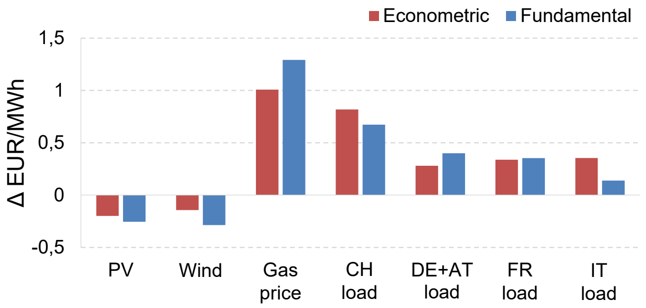

Figure 17: *Electricity price influence factors derived from different economic modeling approaches (EUR/MWh per additional GW; exception: gas price: EUR/MWh per EUR price difference).*

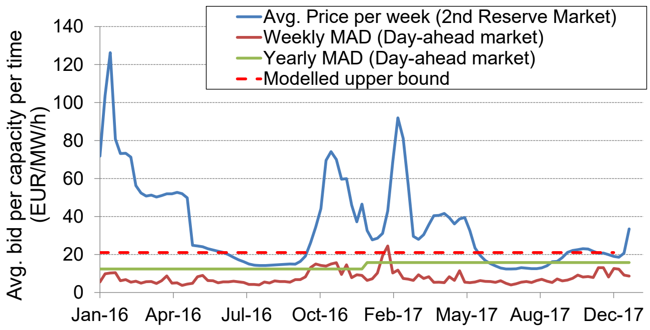

Figure 18: *Secondary Spinning reserve: historical volume-averaged weekly price (blue) and modelled bounds on fair prices: upper bound in case of low hydro availability (red dashed line), and MAD (mean-absolute-deviation of power prices) as lower bound.*

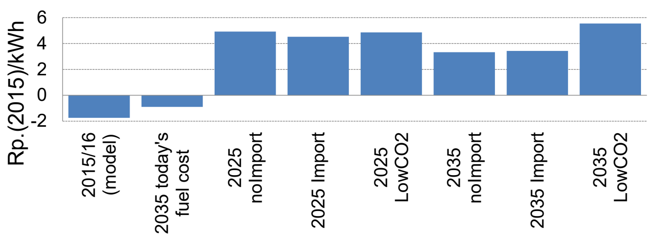

Figure 19: *Scenario-dependent profitability of Swiss hydropower (average market revenues under assumption of 100 % day-ahead trading).*

domestic and German power demand. On the other hand, the increasing deployment of renewables has (at least currently) a magnitude of influence on par with the aforementioned factors (Zimmermann et al., 2018; Keles et al., 2020); see Figure 17.

If the current market integration of Switzerland with the surrounding countries can be maintained (or even enlarged), additional large-scale storage in high renewable scenarios will likely be deployed in Germany, France, and Italy, and not in Switzerland from a pure market perspective (i.e., disregarding national security reasons); see Panos and Densing (2019). This indicates that the profitability of large-scale storage in Switzerland is not secured: If fossil fuel prices stay at today's level, hydropower may not be able to increase its current low profits over a wide range of scenarios (Densing et al., 2018); see Figures 18 and 19. On the other hand, high renewable scenarios assuming increasing fossil fuel prices show that stored hydropower can significantly increase profits by 2035 because of higher price levels, whereas pumped-storage may delay increases until 2050 because high price volatility is expected only relatively late after almost all conventional (non-intermittent) technology is decommissioned (Zimmermann et al., 2018).

Alternative markets, e.g., for ancillary services, are important as an optional source of income, but may not be able to secure hydropower because (i) former high price levels were not at cost (the market is not liquid), and (ii) possible price-ranges in the ancillary market are linked to the wholesale (energy-only) market price volatility (Figures 18 and 19), such that increased market revenues above the wholesale markets will remain limited (Densing, 2020).

3.5 Enhanced Geothermal Systems (EGS)

By Karin Treyer, Warren Schenler & Aleksandra Kim

Geothermal energy in Switzerland is currently dominated by shallow wells used for heat pumps, but according to the Swiss Energy Perspectives 2050+ (Swiss Federal Office of Energy, 2020b) deep geothermal power is supposed to supply 2 TWh per year of electricity by 2050. Globally, deep geothermal generation is dominated by hydrothermal plants accessing hot acquifers at depth. Such resources, however, are presently unknown at a large scale in Switzerland. On the other hand, deep geothermal plants can extract heat from hot rocks at depth via Enhanced Geothermal Systems (EGS). Even though no such plant is currently operating economically worldwide and there is limited public acceptance for EGS in Switzerland, this technology remains an interesting option to provide base-load power and thus help stabilize the power grid. EGS plants make use of the natural temperature gradient in the earth crust, drilling down several kilometers and creating cracks in the rock so that water can be circulated and used for power generation at the surface. EGS plants are technically feasible today, but major uncertainties and challenges remain, including the:

- Success rate of drilling wells (temperature gradient, earthquakes, unforeseen geological conditions and brine composition, etc.)
- Success rate of rock stimulation (flow rate, temperature of heated water and reservoir life)
- Final net capacity of a plant, which depends on technical and plant design choices (e.g., well location, number, and diameter; stimulation technique; flow rate; power cycle).
- Physical and geological uncertainties (e.g., temperature gradient, suitability for reservoir stimulation, etc.) that can only be controlled by plant site selection.

To calculate the environmental impacts and costs of power production of a hypothetical EGS power plant in Switzerland, a physical model was set up and used as integral part of a Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis (Figure 20). The results presented in this deep dive represent a summary of results given in Bauer et al. (2017) and Hirschberg et al. (2015), which include detailed information on assumptions, description of parameters and the cost, physical and LCA models, and results for all Life Cycle Impact Assessment (LCIA) categories.

The EGS plant modelled uses a binary, Organic Rankine Cycle (ORC) system. The physical model of the geothermal fluid circulation includes pressure losses, heat transfer, and fluid density and buoyancy. The model calculates heat production based on well depth, temperature gradient and flow rate, the gross plant power, the production well pump power required, net plant power and co-produced heat.

Based on this model, EGS plants with two wells (doublet) or three wells (triplet) with poor, medium or beneficial geological conditions have been modelled, and the environmental impacts and costs have been calculated based on the inputs from the physical model. For the medium case, well depth is 5 km with a diameter of 8.5 inches (21.6 cm), and the geothermal gradient is assumed to be 30 °C per kilometer. The flow rate varies between 40 to 75 l/s. Reservoir lifetime (a function of geological and technical parameters) is assumed to reach 20 years, and the plant lifetime is set equal to this. Key parameters are changed for the poor and high cases, and sensitivity analysis shows the influence of parameter values on the environmental and economic performance. For the LCC, the interest rate is assumed to be 5 %. Well cost is uncertain due to scarce experience with such wells in Switzerland and also abroad, and depends on well depth, diameter and geology. For LCA, the source and use of energy for the drill rig power are important, with the use also being calculated with a mathematical model. Life Cycle Impact Assessment (LCIA) results have been calculated for 19 impact categories such as climate change, ecotoxicity, ozone depletion, particulate matter formation, or land use.

The Levelized Cost of Electricity (LCOE) and the impacts on climate change for all cases investigated are shown in Figure 21. The average generation cost ranges between 16 and 58 Rp./kWh if the heat from the binary cycle condenser cannot be sold. If this heat can be sold directly to a customer who would otherwise purchase from a district heating grid (at an estimated 7 Rp./kWh for 2000 hours per year), the cost results are much more favorable, ranging between -1.8 and 32.7 Rp./kWh. However, such a case is uncertain. First, the geothermal plant may not be located close to a suitable heat customer. Second, heat revenues might be significantly lower, depending on additional heat delivery grid costs and customer use. Third, any increase in heat temperature for higher value uses is limited, and would significantly reduce electricity generation power. These cost results reflect baseload electricity generation with a possible credit from seasonal heat sales. It is an open question from both the cost and CO_2 perspective whether heat or electricity should be the primary product, and an optimal plant design and seasonal operating balance between heat and electricity will depend upon the particular local geothermal resource and customer mix.

Well construction is by far the largest individual component cost, and also the most important driver in most environmental impact categories assessed, similar to the results shown for the impacts on cli-

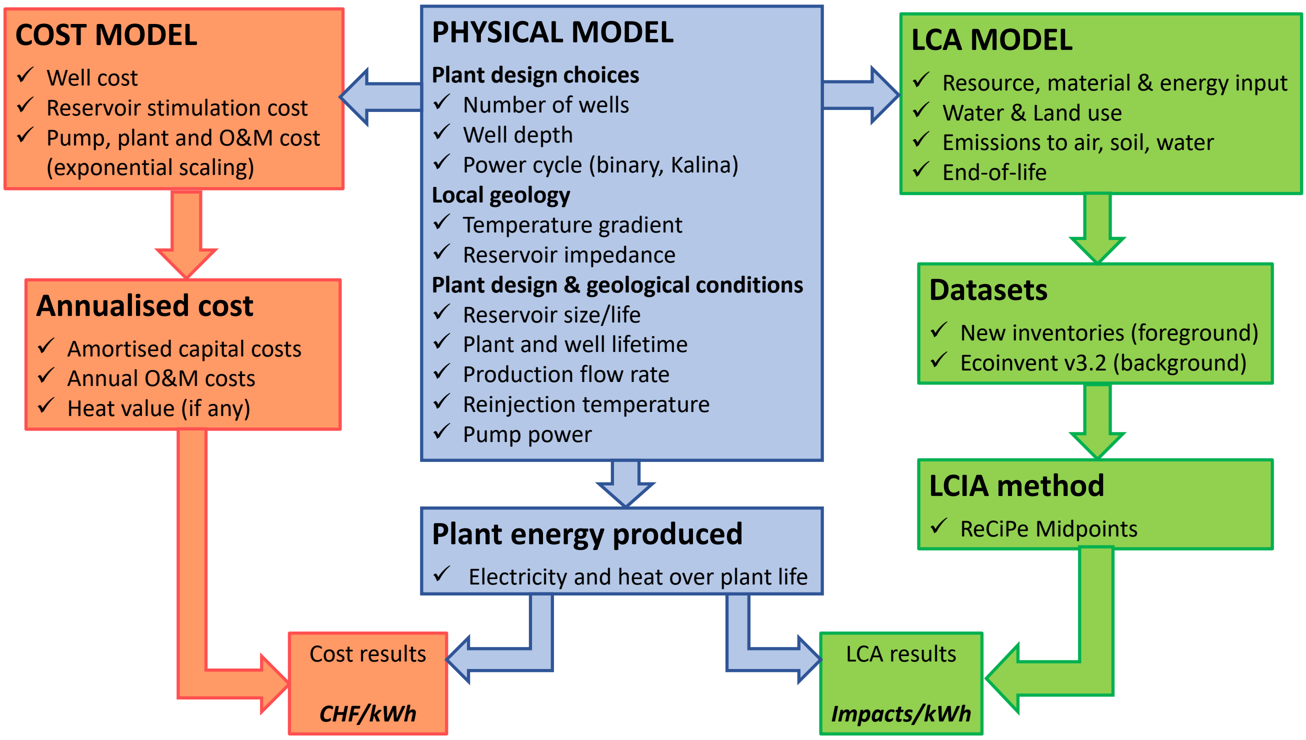

Figure 20: *Scheme of the PSI deep EGS geothermal plant physical model coupled with cost and LCA parameters (adapted from Hirschberg et al. (2015)).*

mate change in Figure 21. Steel and cement use for the casing of the well and the energy input for drilling (Swiss electricity mix with diesel generators as backup) are most important. Total greenhouse gas emissions range between 27 and 84 g CO_2-eq/kWh. For comparison, drilling with today's German electricity mix would double these emissions, while it is expected that the impacts on climate change will decrease with more decarbonized electricity mixes in the future. Life cycle costs could decrease dramatically if new well drilling and reservoir fracturing technologies can be achieved, but these depend largely upon R&D within the much larger oil and gas industry.

A sensitivity analysis for key parameters influencing the net capacity, cost and environmental impacts was performed by varying one parameter at a time. Generally speaking, both the environmental impacts and the costs depend largely on the net capacity of the power plant, so that all parameters with a large influence on the net capacity will have the same effect on the economic and LCA results. These are mainly the gradient and well depth, where a gradient lower than 30 °C/km found by exploration wells would stop the project due to the low expected net capacity of the plant.

The life-cycle environmental impacts of geothermal power generation are highly variable and depend on site-specific conditions. The sensitivity analysis shown above can be extended by applying a Global Sensitivity Analysis (GSA) to the geothermal LCA model. This technique identifies which input datasets used to model the geothermal plant system contribute most to the uncertainty of the LCA results, and hence, for which processes data quality is most relevant for obtaining robust results. Practitioners can then prioritise data collection and focus on acquiring accurate values for only these key datasets for a geothermal plant of interest, while fixing the data in all other datasets within their range of variability. Saltelli et al. (2010) computed Sobol's sensitivity indices and confirmed that installed capacity drives most of the impact variability for all environmental categories in the Environmental Footprint 2.0 method (Fazio et al., 2018). Other relevant parameters include: a) specific diesel consumption per meter of well (diesel burned in a diesel-electric generating set), and b) the average length of wells measured along the actual well path, known as "average measured depth". For these parameters it is not recommended to use values from other power plants as a proxy. Instead, having confident, location-specific values allows an output variance reduction in all impact categories of up to 70 %,

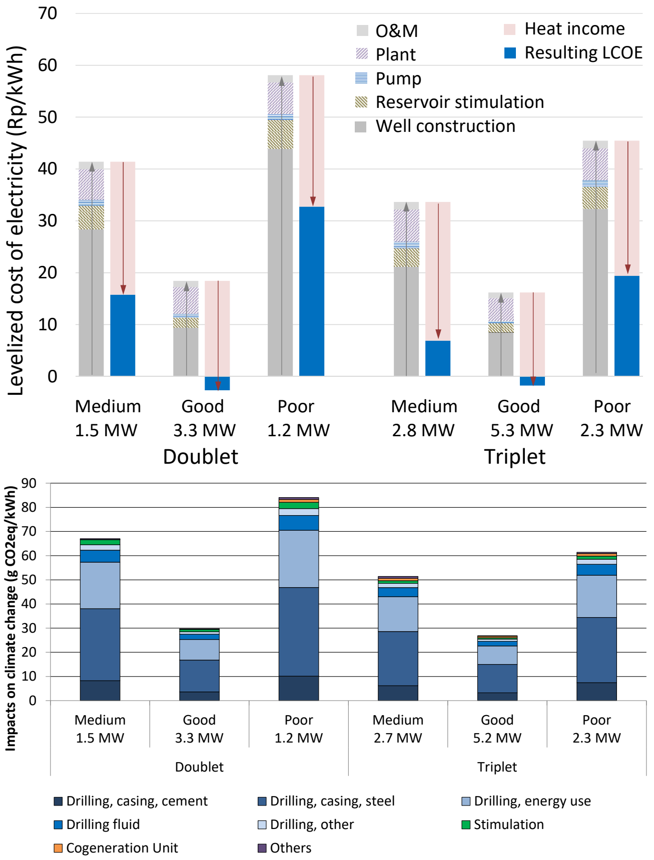

Figure 21: *Levelized cost of electricity (LCOE) (top) and impacts on climate change (bottom) calculated for all investigated cases. O&M = Operation and maintenance.*

10 % and 5 % (for the installed capacity, diesel consumption and depth of wells, respectively). This, in turn, contributes to more informed policy-making.

Results show that it is difficult to predict the capacity of EGS plants, while costs are high if no heat sales are possible. In contrast, environmental impacts are generally lower or in the same range as the Swiss electricity mix and electricity from renewables for economic plants. With the triplet medium case and an associated capacity of 2.8 MWe, yearly production of electricity and heat may reach 23 GWh and 87 GWh, respectively. Thus, about 90 plants with 270 wells would be needed to fulfil the 2 TWh per year target set in the Swiss Energy Perspectives 2050+ (Swiss Federal Office of Energy, 2020b). The corresponding excess heat would exceed the projected district heat demand in Switzerland, which highlights the potential of EGS plants to support both the power and thermal grids.

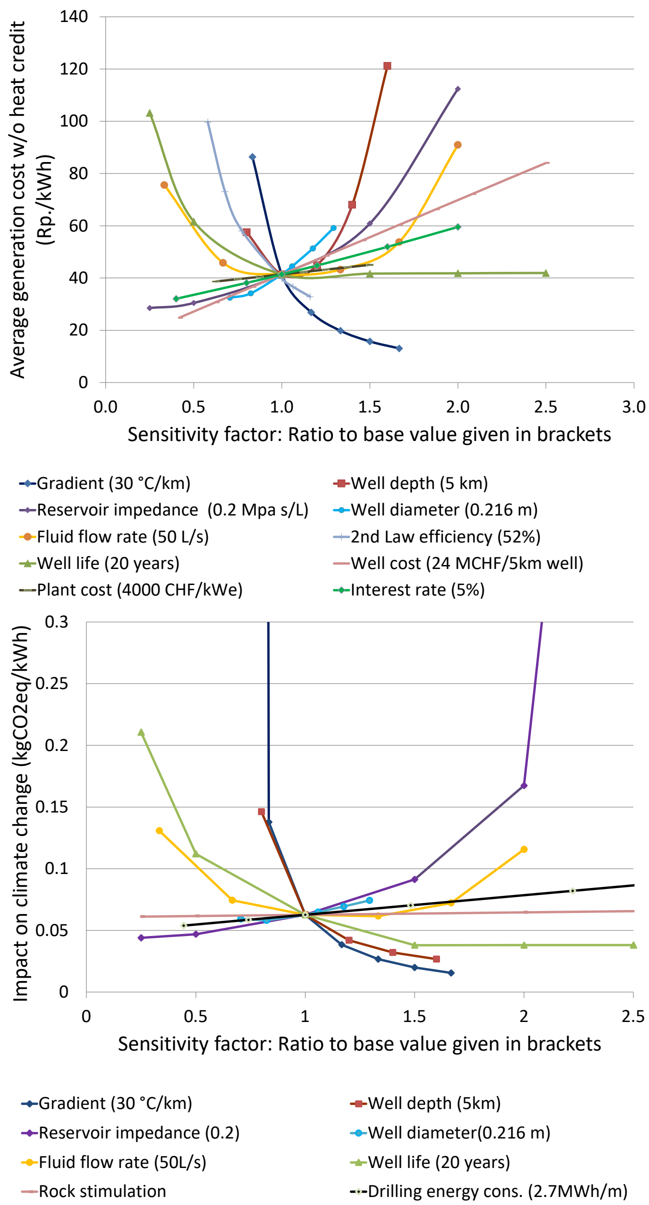

Figure 22: *Sensitivity analysis of key parameters for the levelized cost of electricity (top) and impacts on climate change (bottom) related to the production of 1 kWh electricity.*

4 Challenges and Opportunities

Achieving an electricity supply that is largely based on hydropower and photovoltaics, supplemented by other renewables, quickly enough to achieve climate goals is not straightforward. Challenges are numerous and mastering these will require additional technologies and innovative concepts. However, the transformation holds not only challenges, but also new opportunities, where Switzerland can take advantage.

The main goals of Swiss and European energy and climate policies are clear: decarbonization and a reduction of greenhouse gas emissions towards net zero. How to reach these goals – both in Switzerland and in Europe – is less clear. Substantial challenges remain to be solved. But at the same time, such a transformation of the energy system away from fossil fuels and towards renewable energy sources offers opportunities and co-benefits, which should be exploited.

4.1 Challenges

Speed of Transformation. A transformation of the Swiss energy system – even of the electricity sector on its own, considering the anticipated nuclear phase-out – towards 100 % renewables requires a transformation at an unprecedented pace. Over the last decade, only photovoltaic power generation has expanded in a really substantial way in Switzerland with a growth factor of 40 (in terms of annual electricity generation) between 2009 and 2019. Other renewables exhibited growth factors between two (electricity from wood) and six (wind power) in that decade. However, even the expansion of photovoltaics seems to have slowed down recently.

The trends observed are simply insufficient to achieve the exploitable renewable potentials, which would in fact – on an annual basis at least – probably allow for a 100 % renewable supply within the next 3 decades.

Temporal (and Spatial) Mismatch between Supply and Demand. Even if sufficient renewable power generation capacities were installed to cover of the Swiss electricity demand on an annual basis – a large temporal gap between production and demand would remain. PV generation has daily peaks at noon and seasonal peaks in summer. And since the potential of photovoltaics is higher by an order of magnitude than that of other new renewables, these peaks will shape overall generation profiles and must be compensated by smart site selection, flexibility measures and system integration.

System Integration. As opposed to the current electricity generation system with a few main central power plants, supplemented by decentralized units, a future electricity generation system that predominantly relies on hydropower, PV, wind power and other small-scale renewable conversion units will be decentralized in nature and will require different control mechanisms. Generation from many small sources, spread over space, must be integrated and balanced in order to guarantee grid stability. This requires measures to increase local consumption and a new design for expanding the grid.

Sector Coupling. Measures to deal with seasonal and daily electricity generation peaks also include using this peak generation in sectors of the economy, which are currently hardly electrified, i.e., mobility, industry and the residential sector. Renewable electricity can be converted to hydrogen and further to synthetic liquid or gaseous fuels, which both can be used for indirect electrification of these sectors. Electricity can also be used directly for charging battery electric vehicles, for heat pumps and certain industrial processes. Such a direct and indirect electrification would contribute to a reduction of fossil fuel demand in general, but would increase the overall electricity demand substantially, since conversion losses along conversion chains can be high.

Investment Costs. The transformation of the electricity sector requires large investments. These investments are likely to represent a barrier, even if the gap between levelized costs of electricity from fossil and renewable energy resources is becoming smaller and smaller from a life cycle perspective due to low operating costs. But installing new renewable generation, while also adding the necessary electricity storage, grid reinforcement and sector coupling infrastructure will require substantial investments.

Social Acceptance. Last, but not least, social acceptance represents a challenge to the expanding renewables and achieving their generation potentials as well as to the other new infrastructure required such as transmission lines or large-scale energy storage. Opposition to new wind turbines, expansion of existing or new hydropower plants, or geothermal installations manifests itself again and again in Switzerland. This is due to various reasons: landscape protection, risk aversion as well as potential loss of biodiversity frequently represent reasons for stakeholders to articulate their opposition, often leading to delay or withdrawal of infrastructure projects. An educated consensus on shared priorities will be a necessary precondition for political policy decisions.

4.2 Opportunities

Reduced Import Dependency and Use of Domestic Resources. Increasing the share of renewable domestic electricity generation will reduce dependence on imported energy carriers. However, there may be trade-offs in terms of shifting import dependencies from energy carriers to certain materials or key technologies required for renewable generation technologies, energy storage or sector coupling infrastructure.

Increase of Domestic Value Creation. A shift towards renewable electricity generation will create both high-tech and low-tech business opportunities and could strengthen the job market. Domestically produced renewable electricity can increase domestic value creation. Switzerland, traditionally a high-tech economy, can profit from the needs of new energy technologies. However, innovative approaches and developments will be required. Additionally, transforming the energy system and installing massive amounts of PV modules, batteries, or wind turbines will also create low-tech business opportunities and create local jobs.

Improvement of Air Quality. Direct and indirect electrification of other sectors than power generation will have co-benefits for the environment and human health. Fossil fuels used for heating and vehicles today represent some of the most important sources of air pollution in Switzerland. Replacing these demands by using electricity will thus improve air quality.

Increase of Energy System Resilience. A switch from centralized to decentralized electricity production can – if managed well and supported by appropriate measures for system integration such as demand side management, electricity storage and grid reinforcement – increase resilience of the system.

5 Conclusions and Recommendations

Evaluating technology options for sustainable electricity supply in Switzerland and quantifying their potentials, costs, and environmental burdens represents the sound basis for future energy and climate policy. Photovoltaics will have to play a key role and exploring new solutions beyond the traditional roof-top panels will offer systemic benefits – that much is clear. From the system perspective, however, significant remaining challenges such as energy storage and sector coupling must be investigated with appropriate methods and tools in the future.

Lots of potential – the key role of solar photovoltaic in Switzerland's energy transition

A future electricity supply for Switzerland that will be as climate friendly as today's requires a rapid and large-scale expansion of photovoltaic generation, because this is where the largest potential by far exists for renewable electricity production. The future annual generation potential of solar PV is estimated to be up to 50 TWh/a from building-attached PV systems (BAPV, on rooftops), and 17 TWh/a from building-integrated solar PV systems (BIPV). However, these estimates include substantial uncertainties due to various factors such as temporal variation of solar irradiation, roof geometry and superstructures, as well as the inverse correlation between PV module efficiency and temperature. Therefore, two other recent studies report lower values of 24 $\pm$ 9 TWh/a and 33 TWh/a, respectively. Furthermore, a part of the electricity from photovoltaic plants must be stored for transfer from mid-days to evenings, and from summer to winter. Batteries can supply short-term storage today, but the question of optimal seasonal storage needs further research and other technological solutions. A large expansion of PV generation will also require a corresponding expansion and intelligent operation of the transmission grid.

In addition to solar PV, it is necessary that wind, biomass, geothermal energy and hydropower also achieve their additional potentials and contribute their complementary characteristics. However, diverse social reservations constrain this development. In particular, the estimate of 2 TWh/a generated from deep geothermal systems by 2050 is a policy goal rather than an actual potential. Deep geothermal energy is currently in the research stage, and it is still unclear whether, when and how much electricity this technology will ever produce in Switzerland. Taking into consideration the quite limited total opportunities for domestic, renewable electricity production, it is clear that future electricity demand should not increase. This is an ambitious goal in the face of the trends toward electric mobility, more heat pumps, increasing population, and higher standard-of-living aspirations. Otherwise, Switzerland will probably not be able to do without gas-fired power plants or more electricity imports.

The potential role of the mountains to mitigate the winter gap

Photovoltaic installations in the mountains have the potential to reduce the power deficit experienced by this technology in winter, which also reduces the need for sufficient seasonal storage. The four main advantages of Alpine PV are the following. First, higher solar radiation due to reduced atmospheric absorption and less fog and cloud cover. Second, snow cover leads to an increase in solar energy reflected from the ground. Third, the steep tilt angles of modules offset low winter sun and snow slides off more easily. Fourth, the efficiency of PV systems increases as module temperature decreases due to lower air temperatures and higher wind speeds at high altitudes. Overall, a comparison of urban and mountain scenarios with a total production of 12 TWh/a shows that mountain installations require significantly less surface area and, combined with steeper panel tilt angles, up to 50 % of the winter deficit in electricity production can be compensated. Associated generation and transmission costs need to be further investigated.

Climate risk and the transition to a renewable, low-carbon electricity system

Climate change impacts are often considered as the most crucial, global, environmental concern today. Therefore, greenhouse gas (GHG) emissions represent a key indicator of environmental performance of generation technologies. The current life-cycle carbon footprint is lowest for electricity from hydro, nuclear and wind, followed by wood and solar PV power plants. Life cycle GHG emissions are expected to be lower in 2050 than today for most of the technologies, except that hydro and nuclear power have hardly any improvement potential, with the latter being phased out in Switzerland. Consequently, all renewables are expected to represent low-carbon generation by 2050 with hydro, wind and solar PV performing best. In contrast, natural gas-based generation must be combined with CCS in order to be low-carbon, but it is still not clear yet whether CO_2 storage will ever be feasible given the prevailing conditions in Switzerland – international collaborations should be explored. Lastly, it should be stressed that additional life-cycle based indicators (e.g., resources, toxicity, eutrophication, land use, particulate matter, etc.) need to be considered to obtain a complete picture of the environmental sustainability performance of a technology, and to address potential trade-offs and co-benefits.

Sustainable electricity is worth its price

Current low average generation costs are due to existing hydro and nuclear power plants. For new plants today, some biomass, hydro, large PV and natural gas combined cycle plants would be most economic. For future, new power plants, continuous and substantial cost reductions are expected for solar PV, wind, and fuel cells, while for biomass, hydropower and the other alternatives this is likely not the case. This can be illustrated by the following examples. As soon as more biomass is used, its price in Switzerland will increase, and the same holds true for natural gas according to international trends. Furthermore, the separation and geological sequestration of the CO_2 emissions will bring additional costs for gas power plants, and deep geothermal energy is not yet an economic technology. Overall, electricity supply costs in the future are likely to increase, despite declining costs for some renewables. However, it appears affordable and justifiable for Switzerland as a highly developed and wealthy country to achieve a sustainable, secure and resilient, future power supply.

A holistic perspective to support adaptive policy-making

This synthesis report summarizes two extensive reports that have been prepared for the Swiss Federal Office of Energy (SFOE) on the potentials, costs and environmental assessments of electricity generation technologies, and a subsequent update on electricity generation costs and potentials. These reports provide key technology performance inputs for SFOE's Swiss Energy Perspectives, and support the SFOE's continuous technology monitoring for the Energy Strategy 2050. Although a systemic perspective was not part of these studies, the detailed, technology-specific data serve as essential inputs for activities like the SCCER Joint Activity Scenarios and Modeling (JASM) to explore long-term energy scenarios and to anticipate possible energy transition pathways. In other words, it helps decision and policy makers to explore what might happen, and not what should or we want to happen. Electricity storage needs and hydrogen technologies comprise other crucial components that need to be addressed. For this purpose, the SFOE has commissioned a separate study that provides an overview of technologies relevant for hydrogen production, transmission, storage, and use for re-electrification as well as of selected electricity storage options and their associated costs and life-cycle environmental burdens, for which the final report is expected by mid-2021. Finally, the research activities that were carried out within Innosuisse's SCCER program are being continued within SFOE's new energy research program SWEET (Swiss Energy Research for the energy transition). In the context of the first call for proposal, a consortium led by PSI on "SUstainable and Resilient Energy for Switzerland" (SURE) was awarded funding for six years.

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