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Renewable energy sources: conflicts and opportunities in a changing landscape

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Abstract. Replacement of conventional energy sources with renewables such as solar panels and wind turbines requires adequate land. Impact assessments should be conducted to identify sites exhibiting least conflict with current and future land uses and corresponding ecosystem services. We assessed the electricity potential and geographical distribution of wind turbines and solar panels for current land use and three Swiss land use scenarios. The future scenario A2 with limited construction regulations, a liberalized market and more building surfaces increases the electricity potential for solar panels by 69% from 16.6TWh (potential under current land use and regulations) to a future 28.2TWh. An increase of approximately 26% from solar panels is expected for scenarios B2 (regionalized economy) and trend. Wind-electricity potential could increase by 61% from 93 to 150TWh under A2, and 29% under a B2 or trend scenario. However, whereas the electricity potential for solar panels remains largely unaffected by conflicts with ecosystem services, electricity production from wind could be reduced by as much as 98% due to conflicts with ecosystem services such as "Physical and experiential interaction", "Aesthetic aspects of landscapes" and Habitat and gene pool protection". Depending on the scenario used, low-conflict sites for solar panels and wind turbines could contribute between 85% (trend and B2 scenario) and > 100% (A2 scenario) to the Swiss energy target of 25TWh of new renewable energies by 2050. This includes expected technological developments. Positive impacts of sustainable energy production on regional economies is moderate and will not lead to strong changes in regional economic development.

Keywords: solar panels; wind turbines; electricity potential; land-use change; regional-economic; value added; land use conflicts

Introduction

With the world-energy demand increasing annually by 2%, rigorous transformations of the present energy system will be required worldwide in the coming decades (GEA 2012). The EU has committed to reduce its greenhouse gas emissions to at least 20% below the levels of 1990 by 2020 (EUR-Lex Access to European Union Law 2011), and to achieve a 20% share of renewable energy (RE) (Renewable Energy Directive 2009). Switzerland's RE trajectories are similarly ambitious: 74% of the country's total demand for electricity is set to be covered by renewable sources by 2030. By 2050, 93% should be provided by RE and completely substitute electricity produced by nuclear power (GEA 2012; Kirchner 2012). The feasibility of such goals depends on various factors, e.g., technical advancement improving efficiency (Diouf and Pode 2015), the availability of governmental subsidies (Taylor and Turner 2012) and the extent to which land can be allocated toward renewable energy production (Ramachandra and Shruthi 2007; Stoeglehner et al. 2011; Palmas et al. 2015) without compromising other land uses. RE systems can sometimes be integrated rather easily, e.g. solar panels on buildings (De Schepper et al. 2012; Stoll et al. 2013). However, implementation of renewable energy systems often leads to substantial alterations in the amount and quality of ecosystem services (ES) (Hastik et al. 2015; Moriarty and Honnery 2016). Competition for limited land resources may result in conflicts which reduces the potential for RE production (Pasqualetti 2011; Calvert and Mabee 2015), particularly in a densely populated country with high landscape awareness such as Switzerland (Michel et al. 2015). Thus, if socially accepted and sustainable RE production is the goal, it is key to proactively identify potential changes to ES to preclude land-use conflicts which might affect RE production due to ongoing transformation of European landscapes. This paper provides a comprehensive, spatially explicit conflict assessment for renewable electricity potential (solar, wind) with ES such as e.g. "Physical and experiential interaction", "Aesthetic aspects of landscapes", "Habitat and gene pool protection" or "Heritage and symbolic content" (terminology follows CICES 4.3; Haines-Young and Potschin 2013). The assessment considers major land transformation processes such as urbanization using various scenarios of land change (Price et al.

2015). Specific research questions include: What are future renewable electricity potentials for wind turbines and solar panels in a changing landscape? Where are the potential future conflicts with other land uses? What is the relative order of magnitude of future electricity potentials given advancements in technology and considering changes in suitable area for solar panels and wind turbines due to land change? What are the impacts of renewable electricity potential on economies of rural communities which are more susceptible to changes in land use due to their remoteness?

Material and methods

Study areas

This study has two spatial extents (Fig. 1):

(1) *The entire Swiss territory for the conflict analysis*: Switzerland covers an area of approximately 4.1 million ha (SFSO 2013). Settlement areas cover 7.5%, agriculture 35.9%, forests 31.3% and unproductive land 25.3% of the total area (SFSO 2013).

(2) *Four rural study areas for the economic assessment*: Rural areas share some common properties: they have a high share of population employed in the primary sector, a high share of residents >65 years, and a low tax revenue per capita (SFSO 2013). The following areas were found to be typical examples for Switzerland: Emmental (33,060 ha, Northern Alps), Goms (65,020 ha, Central Alps), Surselva (147,370 ha, Central Alps) and Val de Ruz (12,850 ha, Jura Mountains; Fig. 1).

Current electricity potential

Solar panels

The physical electricity potential (PEP; Fig. 2) for solar panels on roofs is calculated by multiplying a solar radiation map with the area covered by buildings. PEP is reduced to LEEP (electricity potential considering economic and legal factors) by taking into account economic, legal, technical, or social factors (Cattin et al. 2012; Table 1, Fig. 2). The proportion of households willing to install solar panels was assumed to be 60% for buildings >1000m² (140km²) and 40% for smaller buildings (405km²).

These estimates follow assessments of Solarserver (2016), Henning and Palzer (2012) as well as own observations. Factors reducing PEP varied between flat and steep roofs. Flat roofs require elevated panel tracks reducing the suitable roof area due to shading. Steep roofs are more prone to shading due to unsuitable north- and east-facing roofs. Additionally, roof area was reduced because of chimneys or dormers on both roof types. Solar panels on facades are currently rare and therefore supplement our estimations only for future electricity estimations (Table 1).

Wind turbines

The physical wind-electricity potential (PEP; Fig. 2) relied on a map of wind speeds, assuming wind speeds >4.5m/s necessary for turbines built on flat, stable ground (Cattin et al. 2012; Table 2). Settlement areas, groundwater protection areas and legally protected landscape and nature protection sites¹ reduced the suitable area for placing wind turbines (Table 2). Suitable areas were represented by points on a 25x25m grid to calculate the maximum number of wind turbines following Lütkehus et al. (2013). A turbine was placed at the point featuring the highest wind speed within the suitable area. To avoid interference, all points within a distance of 456m (for turbines with a hub height of 120m) of the turbine were then excluded from the suitable area. This procedure was repeated until no more turbines could be placed. Finally, a mean yearly output of 5GWh per turbine was used to calculate LEEP. For central European conditions this constitutes the lower end of the mean yearly production potential (Akademien der Wissenschaften 2012).

Future electricity potential

Technological improvements

To assess the magnitude of expected improvements in solar and wind technology, we conducted semi-structured interviews with leading experts from key institutes and businesses for RE in Switzerland (PSI - Paul Scherrer Institute, Villigen, ZHAW - Zurich University of Applied Sciences,

¹ Nature protection sites are not an exclusion criterion for scenario A2

Wädenswil, and Kohle & Nussbaumer SA, Lausanne). The interviews focused on likely technology improvements in the next 20 years.

Land-use change scenarios

To understand the potential extent and magnitude of future changes in land use and associated ES, we employed the model-based, spatially explicit Swiss land-use scenarios by Price et al. (2015) without modification. These scenario storylines were based on socio-economic developments for Switzerland up to 2035 (Price et al. 2015) and were implemented using a spatially explicit modelling framework (Verburg and Overmars 2009). *Current* land use was determined by the Swiss land use statistics 2009 (SFSO 2013). Delineation of a *trend scenario* was based on a linear projection of observed past land-use transitions (1985-1997-2009) into the future (2035). The *A2 scenario* was a growth and pressure scenario where a liberalized economy ceases to support direct payments for extensively managed agriculture or nature conservation and imposes few planning restrictions. Rather, increased agro-technological innovations lead to highly intensified agricultural land use, neglecting spatial planning aspects. In contrast, the *B2 scenario* relied on self-sufficiency and development at the regional level paired with increased ecological sensibility. Compared to 2009, all scenarios showed an increase in forested (trend/B2: +<1%, A2: +3.4%) and urban area (trend: + 11%, B2: +16%, A2: + 60%). Arable land consistently decreased in all scenarios (trend: -5%, B2: -1%, A2: -15%). While pastures also decreased in trend (-4%) and A2 (-16%), the area was maintained in B2 (Price et al. 2015).

Sensitivity analysis

While our assessment relied mostly on empirical values as taken from METEOTEST (Cattin et al. 2012), various assumptions and uncertainties are inherent to our estimations. We identified uncertainties related to electricity estimations and the electricity distribution as particularly relevant. A sensitivity analysis (SA) was performed for parameters not relying on empirical or published values as in METEOTEST (Cattin et al. 2012). The SA was calculated for the current and the most extreme land use scenario A2. For solar panels in 2009, three parameters were subject to the SA: proportion

of installed panels for both large and small roofs, and panel efficiency (Table 1). Two additional parameters were applied for facades: proportion of installed panels and panel efficiency (Table 1). The range of values accounted for was $\pm 20\%$ of the assumed default value. For panel efficiency, the default values were assessed plus 20% only. For wind turbines, the minimum distance of 300m around inhabited area was subject to the SA (100m, 500m; Table 2).

Conflicts with ecosystem services

On the whole, this section follows Egli et al. (2016), Hastik et al. (2015), and Kienast et al. (2016). For solar panels on roofs and facades, we identified a potential conflict with objects of high cultural importance or heritage value. Such objects are often subject to strict regulations on construction measures which preclude installation of solar panels. We used three inventories containing information on buildings with cultural importance (Table 3) to map the ES "*Heritage and symbolic content*". The more of such buildings are present at a site, and the higher the legal protection status the higher the ES supply and the stronger the potential conflict with (traditional) solar panels. Table T1 (Appendix) provides information on how inventory data was transformed to standardized ES values.

For the placement of wind turbines in landscapes, we identified four potential conflicts with ES (Table 4): (1) ES "*Physical and experiential interaction*": Tourism/recreation, a major contributor to the Swiss economy, is sensitive to the placement of turbines due to potential negative effects on visitors (noise, aesthetics). The ES was mapped using several indicators, including *nearby recreation*, a model-based, spatially explicit extrapolation of a representative survey in six Swiss towns (Kienast et al. 2012; Buchecker et al. 2013). *Further indicators include* a set of attractive landscape characteristics (Table 4), and overnight stays (BFS, 2016) to approximate *long-term tourism*.

(2) ES "*Habitat and gene-pool protection*": Turbines might cause conflicts with wildlife protection. This ES was represented by conservation reserves, protected areas and maps of particularly vulnerable species (Table 4).

(3) *ES "Aesthetic aspect of landscapes"*: Aesthetic aspects may prevent the placement of turbines (Kienast et al. 2015). Though beautiful landscapes are an important driver of tourism, it is certainly not the only one. Thus, we kept this ES clearly separated from the ES "Physical and experiential interaction". To map the ES, we used the inventory of landscapes and natural monuments of national importance (ILNM) and the Swiss-wide indicator perceived landscape beauty from the Swiss Landscape Monitoring Program LABES (Table 4).

(4) *ES "Provision of food and fiber"*: Wind turbines might slightly interfere with provisioning services such as food or fiber, approximated with the area of intensive agriculture and forest (Table 4). Concerning food production the poles of wind turbines might prevent agricultural machines from operating with efficiency. Due to the fact that the farmer is compensated for his/her allowance to place the wind turbine on the field, there is less incentive to produce food, a potential slight conflict. The conflict with forest concerns loss of area due to road access and gap opening.

Each ES map is a composite map (sum) of several spatially explicit indicators described in Tables 3 and 4. Depending on the number of indicators, the range of values of the resulting ES maps differ considerably among the ES. In order to generate comparable maps, the resulting data have been standardized. Table T1 (Appendix) provides information on the standardization applied. As a rule, low standardized values (0, 1) indicate no or low supply of an ES, while high values (2, 3) indicate high supply of an ES for any given pixel. The standardized ES maps were spatially intersected with the LEEP maps, generating conflict maps: LEEP areas intersecting with areas of no ES supply (value "0") were flagged as *no conflict sites between ES and electricity potential* (Appendix Table T1).

Intersections between LEEP areas and low ES supply (value "1") are considered *low conflict sites*. LEEP areas on sites with medium ES supply (value "2") are flagged as *strong conflict sites*, whereas intersections between LEEP areas and sites with high ES supply (value "3") reveal potentially *very strong conflict* between ES and electricity potentials. A similar procedure to convert ES into conflicts was applied by Kienast et al. (2016).

Electricity potentials and conflicts under land-use change

Solar panels

For all future scenarios, we added the LEEP from facades (Table 1) to the LEEP of solar panels on roofs. Further, any new pixel becoming urbanized due to one of the land-use change scenarios A2, B2 or trend (Price et al. 2015) was equipped with solar panels (facades and roofs) according to the mean building characteristics and settlement structures within a radius of 1000m of the respective pixel. Any pixel became suitable for the placement of solar panels when the criteria in Table 1 were fulfilled.

Wind turbines

The interviewed experts estimated the yearly output per turbine to increase to 6.5GWh. This value was thus used to assess the future LEEP of wind turbines. Any pixel became suitable for the placement of a wind turbine when the criteria in Table 2 were fulfilled².

Potential future regional-economic impacts

Future potential regional-economic impact for the study areas was assessed by calculating direct gross value added (GVA), i.e. value added when producing energy including planning and construction of infrastructure and equipment. Indirect impacts from input goods and services and induced or catalytic impacts on e.g. consumption and income were not taken into account. We followed Ribi et al. (2012), who calculated direct GVA generated by individual renewable energy plants over their entire lifetime in selected rural regions in Switzerland. The calculation of the direct GVA was based on estimated electricity sales for 2035, where sales equaled expected electricity costs (Table 5) multiplied by the electricity potential of the region as estimated in this study. Electricity costs were estimated based on mean production costs over the entire lifetime of a plant including investment and operating costs. Estimated sales were then divided into direct GVA and indirect GVA based on percentages estimated in previous studies for Switzerland (SATW 2006; Infrac 2010) and on

² Nature protection sites are not an exclusion criterion for scenario A2

additional assumptions (Table 5). Estimated direct GVA equaled 46.85% of gross GVA for wind and 37.55% for solar electricity. Further, direct GVA was subdivided into direct GVA generated abroad, within Switzerland and within the rural study area. These percentage share of sales were based on the input-output table in the Swiss national income accounting (BFS 2008). Regional value added share was calculated by dividing direct GVA generated in the region by the total regional GVA. The latter was estimated using Ribí et al. (2012). Total GVA (not adjusted for inflation) in Emmental, Goms, Surselva and Val de Ruz was calculated to be 1099, 213, 953 and 300 million CHF in the base year 2010, respectively.

Results

Conflicts under land-use change

Solar panels

On a national scale, the LEEP for solar on roofs was approximately 16.6TWh in 2009 (Table 6). The A2 scenario shows the strongest increase in LEEP (+69%) compared to 2009, followed by the B2 (+29%), and the trend scenario (+25%). Electricity potentials exhibiting low-conflicts with ES were high for current and future land use and around 94% of the particular LEEP. The nationwide contribution of building facades to LEEP was about 10% for all future scenarios.

At the regional scale, however, the pattern was more divergent (Table 6). LEEP on new settlement areas having a settlement structure similar to adjacent existing settlement areas were strongest for Val de Ruz (A2: +128%, B2 +57%, trend: +20%) and Emmental (A2: +130%, B2: +49%, trend: +19%). For Surselva, new settlement had a moderately positive impact (A2: +36.6%, B2: +33.3%, trend: +24.2%), whereas Goms exhibited an electricity gain of ca. 28% independent of any scenario. Facades contributed most to the solar LEEP in Goms (+18-20%) and Surselva (+17-18%), and were comparably low for Emmental and Val de Ruz (+11%-13%). Proportions of low-conflict electricity of the LEEP were highest for Emmental and Val de Ruz.

Wind turbines

Nationwide current LEEP for wind electricity equaled 93.4TWh, corresponding to 18,675 turbines (Table 7). LEEP was reduced by 98.7% to 1.2TWh when considering only turbines located in sites with low-conflict potential. Under the trend and B2 scenarios, LEEP increased by 28% to 120TWh. For A2, the increase was substantially more pronounced (+70%). However, the relative reduction through conflicts meant all future scenarios remained comparable to the current situation. Strong and very strong conflicts were highest for the ES “Aesthetic aspects of landscapes”, followed by “Habitat and gene pool protection” and “Physical and experiential interactions” and lowest for “Provision of food and fiber” (Fig. 3).

Surselva had the highest current LEEP of the rural study areas (Table 7). For Emmental, Goms and Surselva, there were strong conflicts with “Aesthetic aspects of landscapes” (potential reduction up to 100%, very strong and strong conflicts; Fig. Appendix A1). Conflicts with “Provision of food and fiber” were lowest. Under scenarios of land-use change, the impacts of conflicts with the ES remained proportionally the same as for 2009 (Appendix Figs. A2-A4). Given the A2 scenario, Surselva will profit most with an increase of +117% of the current LEEP, followed by Emmental (+43%), Val de Ruz (+40%) and Goms (+35%; Table 7).

Technological improvement

According to the expert interviews, wind turbines will be more effective at low wind speeds by 2035. This technological improvement will increase the yearly electricity output per wind turbine by up to 16% to range between 6.5-8.5GWh. Also, turbines will become easier to transport and assemble, making installation in remote areas more likely. According to the experts, solar panels may still rely on crystalline cells in 2035, but average efficiency will increase by at least 20%. Developments may include panels in different colors, organic materials and more flexible forms. This may lead to higher aesthetic acceptance and allow placement on many surface types. Panels on facades are expected to have an average efficiency of ca. 15%.

Regional-economic impacts

For solar electricity, low conflict regional value-added share ranged from 0.18 to 0.38% and was lowest in Emmental (Table 8). For the other study areas, low-conflict value-added share was approximately 0.30%. For wind, value-added share of LEEP was 2.91- 23.73%. Considering only the low-conflict potential, value-added share was 0.33- 4.63%. Only direct economic impacts were taken into account, therefore total regional-economic impact is expected to be higher.

Sensitivity analysis

Sensitivity analysis of non-empirically derived parameters for solar panels revealed that the range of electricity potentials was at least twice as high between land-change scenarios as within scenarios (Appendix Tables T2-3). This indicates that the land-use change effects considered exceeded uncertainties originating from electricity estimations. The same is observed for the placement of wind turbines in low-conflict areas for 2009 – the sensitivity to land-use change scenarios exceeded effects of the variation in buffer size for precluding the placement of turbines around settlements (Appendix Tables T4-5). However, for large buffer sizes (500m) in the A2 scenario, the effects of the buffer size exceeded the impact of land-use change on the low-conflict electricity production from turbines (Appendix Tables T4-5).

In the study areas, the effects of land-use change scenarios exceeded the effects of the variation introduced by non-empirical parameters when assessing low-conflict electricity potentials for solar panels (Appendix Tables T2-T3). Similarly, the low-conflict potential of wind electricity responded more strongly to the scenarios than to the variation introduced by buffers around settlements (Appendix Tables T4-T5).

Overall, we conclude that effects of land-use change affect low-conflict electricity production more than uncertainties in the assumed values of the non-empirical parameters as outlined in Tables 1, 2, 3 and 4.

Discussion

Current and future electricity potentials

While changes in land use may provide new opportunities for the placement of RE infrastructure, competition for limited land resources may generate conflicts counteracting the RE potentials in a densely populated country (Calvert and Mabee 2015; Moriarty and Honnery 2016). As highlighted by our comprehensive conflict assessment for current and potential future land use, spatial constraints are important determinants of RE potentials. Currently the acceptance of RE affecting landscape aesthetics, particularly wind energy, is low in Switzerland, potentially related to high sensitivity to tourism impacts and landscape issues (Michel et al. 2015; Grilli et al. 2016). The current LEEP from wind turbines in Switzerland is five times higher (93.4GWh) than that from solar panels (16.6GWh), increasing further in future scenarios. However, the electricity-potential reduction due to conflicts with ES may almost completely preclude the production of wind power - also given future land-use change, in spite of technological developments. Environmental concerns primarily refer to the protection of habitat and species, whereas aesthetics and tourism both relate to people's perceptions. While conservation concerns will likely persist (Smallwood 2013), people's attitudes towards wind turbines may be dynamic (Wolsink 2007). Although the major reason for resistance to wind turbines relates to landscape change (Pasqualetti 2011), the significance of visual impact may be outweighed by long-term economic benefits (Frantal 2015). Changes in attitude from critical to positive are usually caused by personal experience of working turbines (Kontogianni et al. 2014). The low acceptance of wind turbines might therefore be overcome by increasing people's awareness of the turbine's benefits, particularly considering developments towards bladeless, quieter wind turbines (Patel 2015) which might also mitigate conservation challenges in the long term. In contrast, the current LEEP of solar panels on roofs was reduced by only 5% due to conflicts, amounting to a total of 15.4TWh; a value in the same range as other sources suggest (15.5TWh (Cattin et al. 2012); 11.1TWh (Kirchner 2012)). Solar panels could thus *currently* contribute 61.6% to

the overall Swiss energy target of 25TWh new RE by 2050. Under future land-use change, in particular under the A2 scenario, electricity production from solar panels will strongly profit from urbanization and even exceed the Swiss energy target by 106% (26.6TWh; Table 6), whereof ca. 11% will originate from solar panels on facades). Given the assumptions underlying the A2 scenario, the Swiss energy target of 25TWh could be met alone by equipping roofs and facades of current and future buildings with solar panels. In addition, the willingness to adopt photovoltaic installations is high with increasing tendency towards cheaper devices (Korcaj et al. 2015). Simultaneously, developments to efficiently integrate new generations of photovoltaic devices into roofs, skylights, or facades are advancing fast (Cornaro et al. 2015). The electricity production from solar panels could thus profit enormously from new settlement areas. Although seemingly favorable in the context of RE, urbanization, however, has many problematic energy, environmental and societal consequences which are discussed elsewhere in detail (Wissen Hayek et al. 2011; Jaeger and Schwick 2014). However, assuming a *total* energy consumption of 60 - 250 GJ per person and year (Grubler et al. (2012), the energy generated in the newly built settlements would provide enough energy for 100'000 to 500'000 people. This is between 7 and 40% of the expected population increase by 2035 in Swiss urban and periurban areas (BFS, 2016).

Regional-economic electricity potentials

Out of the different regional energy strategies, export-oriented strategies for energy or energy technologies and services are expected to generate the most revenue and to increase direct regional-economic impacts (Raupach-Sumiya et al. 2015). Swiss regions with hydropower potentials follow this strategy successfully (Ribi et al. 2012). In contrast, regions not currently benefitting much are interested in increasing energy self-sufficiency and independence from price volatilities by transforming their regional energy system to renewable sources and by producing electricity or heat only for regional needs. As most Swiss regions follow the latter strategy, future regional-economic prospects will continue to be rather modest. Nevertheless, due to regional investments, this strategy prevents the outward flow of financial resources. Thus, future energy prices in the region are

expected to be lower. However, the regional economy usually does not benefit from that strategy because the creation of added value is limited to a rather small regional home market. Future economic prospects in the renewable energy context are better for regions which manage to export energy as well as technologies and services (Kosfeld and Gückelhorn 2012). However, Swiss rural regions, as other peripheral rural regions in Europe, are small and often lack infrastructure for entrepreneurship and start-up of new businesses (Baumgartner et al. 2013).

To what extent RE potentials can be valorized depends largely on the development of energy prices (Heinbach et al. 2014). Taking for granted that energy prices will continue to rise in the future, regional-economic prospects might slightly increase. Looking at different RE and the distribution of GVA shares, regions with other RE potentials not taken into account in this study, e.g. wood and biomass potentials, will probably benefit more than regions with wind and solar potentials, although the major share of GVA for wind and solar potentials will accumulate in regions producing these technologies.

Limitations and uncertainties

The approach to map ES relies on look-up tables which are widely used and well suited for comprehensive, large-scale assessments (de Groot 2006; Kienast et al. 2009). Kienast et al. (2009) discussed use and limitations of the approach and concluded that service mapping with other methods such as sophisticated process models only makes sense for well-studied services and processes (e.g. CO₂ flux, agricultural production). As outlined in Grêt-Regamey et al. (2015), not enough process knowledge is available to build spatially explicit mechanistic ES models with the services explored in this paper. Therefore, our assessment methodology is in line with recent research building on multi-criteria decision-making and spatial decision support to map conflict potentials (Kienast et al. 2009). We are well aware that the look-up table approach using cumulative indicator maps to estimate ES supply requires a transparent data handling which includes careful selection of the indicators and standardization of the data (Table T1, Appendix).

Electricity from solar and wind are among the main sources for RE (de Castro et al. 2011, 2013). However, published estimates assessing their potentials vary greatly (Moriarty and Honnery 2012, 2016). On the one hand, this uncertainty roots in, for example, various technological developments or energy losses associated with the conversion to electricity, complex spatial distribution of wind and radiation in a changing climate, or changes of wind speeds when consecutively passing several turbines in a wind park (de Castro et al. 2011, 2013; Moriarty and Honnery 2012, 2016). On the other hand, estimates for energy potentials are also a function of the spatial scale considered: potentials from solar panels and wind turbines are generally lower in top-down approaches compared to bottom-up approaches (de Castro et al. 2011, 2013). Simultaneously, the socio-cultural context may influence estimated electricity potentials (Hastik et al. 2015). While solar panels mounted on facades and roofs may only trigger minor conflicts with aesthetics (De Schepper et al. 2012; Stoll et al. 2013), ground-mounted solar parks are less accepted (Tsoutsos et al. 2005; Michel et al. 2015; Grilli et al. 2016). In line with Cattin et al. (2012), we did not assess the placement of solar panels on open land. Reasons for this root in the generally high landscape awareness in Switzerland (Kienast et al. 2004; Hastik et al. 2015), e.g., for the vulnerability of the fragile Alpine environment (Grilli et al. 2016), resulting in reduced acceptance of solar parks on open land (Michel et al. 2015).

Conclusions

Our assessment can help delineating the feasibility of reaching the Swiss energy target of 25TWh/y by 2050 through renewable energies. It highlights that future land use and conflicts with ecosystem services are important drivers for the placement of renewable energy infrastructure in landscapes. The study has three major findings that are relevant for research and practice:

1. *Solar panels profit from urbanization*: Increase of settlement areas, combined with a smart city approach and modern housing technology (insulation, solar panels on roofs and facades) can significantly contribute to the Swiss energy target. Solar panels could *currently* contribute 61.6% to the overall Swiss energy target of 25TWh by 2050 through RE. If equipped with solar panels on roofs

facades the newly urbanized areas assumed in all scenarios could contribute as much as 77% up to 106% of the Swiss energy target of 25TWh. For a critical assessment of urbanization issues see discussion section.

2. Wind energy is highly conflicting with ecosystem services: Conflicts with ecosystem services and negative perceptions of wind turbines (NIBY phenomenon) strongly reduces the wind-energy potential. Therefore, mitigation of land-use conflicts (combined with technological advancement) should be the major goal of wind-related energy policies.

3. Positive impacts of sustainable energy production (solar panels, wind turbines) on regional economies is moderate: Regional-economic impacts of electricity production originating from solar panels and wind turbines are expected to be moderate and will not fundamentally change regional economies.

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 559

560 **Figure captions**

561 **Figure 1:** Spatial distribution of the current electricity potential for (a) solar panels and (b) wind
562 turbines in Switzerland (dark areas) and the location of the four rural study areas for regional-
563 economic assessments.

564 **Figure 2:** Definition of electricity potentials.

565 **Figure 3:** Wind-electricity potentials [TWh] and conflicts with ES for current (2009, top left) and
566 future scenarios of land-use change (A2, top right), B2 (bottom left), trend (bottom right). * ES
567 "Provision of food and fibre": low conflict with wind turbines on intensive agricultural land, strong
568 conflict with forest.

569

570 Table 1: Parameters reducing the physical electricity potential (PEP) of solar panels on roofs and
571 facades.

Assumptions	Remarks	Spatial data source	Sensitivity analysis ^a
On building roofs (following Cattin et al. 2012)		swissBUILDINGS ^{3D} 1.0 © 2015 Swisstopo (5704000000)	
1) Roof size > 1000 m ² : Proportion of installed panels: 60%	Willingness to install		48% and 72% (±20% of the default value)
20% steep roofs. Of this, 50% with suitable incidence angle. Of this 80% with suitable roof structure			
80% flat roofs. Of this, 50% with suitable roof area. Of this	Excluding north- and east-facing roofs. Excluding chimneys, dormers, etc.		
80% with suitable roof structure	Excluding areas needed for elevated panel tracks and gaps to avoid shading. Excluding chimneys, dormers, etc.		
2) Roof size < 1000 m ² : Proportion of installed panels: 40%	Willingness to install		32% and 48% (±20%)
60% steep roofs. Of this, 50% with suitable incidence angle. Of this 50% with suitable roof structure	Excluding north- and east-facing roofs. Excluding chimneys, dormers, etc.		
40% flat roofs. Of this, 50% with suitable roof area: Of this, 50% with suitable roof structure	Excluding areas needed for elevated panel tracks and gaps to avoid shading. Excluding chimneys, dormers, etc.		
3) Panel efficiency is 20%	Radiation driving solar panels		24% (+20%)
4) Local mean annual solar radiation		Global irradiation - annual mean 1981- 2000 © METEOTEST (Cattin et al. 2012)	
On facades^b (based on expert interviews)		swissBUILDINGS ^{3D} 1.0 © 2015 swisstopo (5704000000)	
1) Proportion of installed panels: 30%	Willingness to install		24% and 36% (±20%)

2) 30% of building facades is suitable	All buildings are cuboid-shaped with maximal one facade per building equipped with solar panels (incidence angle, budget)	Only facades > 2 m above ground are equipped due to low radiation near ground	18% (+20%)
3) Panel efficiency is 15%	Radiation driving solar panels		Global irradiation - annual mean 1981-2000 © METEOTEST (Cattin et al. 2012)
4) 65% of the local mean of annual solar radiation			

572 ^a Solar facades were only considered for future assessments on solar electricity

573 ^b Performed for parameters not relying on empirical or published values as in METEOTEST (Cattin et
574 al. 2012)

575 Table 2: Parameters reducing the physical electricity potential (PEP) of wind turbines.

Assumptions	Spatial data source	Sensitivity analysis ^a
Physical factors (following Cattin et al. 2012) <ul style="list-style-type: none"> • mean wind speed 100 m above ground > 4.5 m/s • stable soil • exclusion of water bodies • slopes < 20% (flat to gradually sloping terrain) 	Map of wind speed, Switzerland © METEOTEST 2015; swissTLM ^{3D} 1.2 © 2015 swisstopo (5704000000); dhm25 © 2015 swisstopo (5704 000 000);	
Legally protected landscapes (following Cattin et al. 2012) Exclusion of all mire landscapes, raised bogs, fenlands, core zone of the national park and nature parks buffered with 200m	Flachmoore, Hochmoore, Moorlandschaften, Pärke © BAFU, 3003 Bern	
Inhabited area (based on Cattin et al. 2012) Settlements buffered with 300m	NOAS04 © 2014 Bundesamt für Statistik (BFS), GEOSTAT	100m, 500m
Groundwater protection (following Cattin et al. 2012) Exclusion of all groundwater protection areas	Data provided by cantonal agencies (date 2014)	
Protected nature reserves^b (based on Hergert 2013) Exclusion of all cantonal nature reserves	Various data provided by federal and cantonal agencies	

^a Not excluded for the land-change scenario A2

^b Performed for parameters not relying on empirical or published values as in METEOTEST (Cattin et al. 2012)

580 Table 3: Ecosystem services potentially conflicting with solar panels.

Ecosystem service (CICES)	Data for mapping (indicators)	Spatial data source
Heritage and symbolic content	World Heritage cultural sites (buffered with 300m)	Welterbe © 2015 Bundesamt für Kultur (BAK)
	Objects of cultural importance (castle, church, tower, monument)	Vector25 © 2015 swisstopo (5704000000)
	Federal Inventory of Swiss Heritage Sites (ISOS) (buffered with 300m)	Bundesinventar ISOS © 2015 BAK

581

582 Table 4: Ecosystem services potentially conflicting with wind turbines.

Ecosystem service (CICES)	Data for mapping (indicators)	Data source
Physical and experiential interactions (tourism, recreation)	<ul style="list-style-type: none"> • Map of the nearby recreation potential 	Kienast et al. 2012
	<ul style="list-style-type: none"> • hiking, skating and bike trails • paddle trails • slow-up 	SchweizMobil © 2014
	<ul style="list-style-type: none"> • ski lifts and cable cars • areas > 1,000 m asl • huts • inns, castles 	swissTLM3D © 2015 swisstopo (5704000000)
	<ul style="list-style-type: none"> • Overnight stays in hotels in the year 2000 (communal level) 	Overnight stays 2000 © BFS
	<ul style="list-style-type: none"> • national park and nature parks 	Pärke © BAFU, 3003 Bern
	<ul style="list-style-type: none"> • Federal Inventory of Swiss Heritage Sites (ISOS) 	Bundesinventar ISOS © 2015 Bundesamt für Kultur (BAK)
	<ul style="list-style-type: none"> • lake landscapes • touristic landscapes 	INFOPLAN-ARE Landschaftstypologie Schweiz © Bundesamt für Landestopografie
	<ul style="list-style-type: none"> • Map of conflict potential wind energy and breeding birds, visitors and bird reserves according to the list of reserves for waterfowl and migratory birds in Switzerland (WMBRs (Horch et al. 2013)) • Model based bird migration sensitivity map (Liechti et al. 2013) • Alluvial zones of national importance • Amphibian spawning areas of national importance • Dry grasslands of national importance • Emerald areas • Federal game reserves • Forest reserves • Ramsar sites 	© 2013, Swiss Ornithological Institute, Sempach Protectorates and biotope inventory © BAFU, 3003 Bern
Aesthetic aspects of landscapes	<ul style="list-style-type: none"> • Perceived landscape beauty 	Kienast et al. (2015)
	<ul style="list-style-type: none"> • Federal inventory of landscapes and natural monuments of national importance (ILNM) 	© BAFU, 3003 Bern
Provision of food and fiber	<ul style="list-style-type: none"> • Forest 	NOAS04 © 2014 Bundesamt für Statistik (BFS), GEOSTAT
	<ul style="list-style-type: none"> • Intensive agriculture 	

583

584

585 Table 5: Parameters to assess the regional-economic electricity potential from solar panels and wind
586 turbines (Ribi et al., 2012). Other renewable energy sources (*) are shown to compare orders of
587 magnitude.

	Photo- voltaic	Wind energy	Large-scale hydropower plants*	Small hydropower plants*	Wood (heat)*	Biomass without wood (electricity)*
Expected costs 2035 [CHF/kWH]	0.16	0.19	0.13	0.18	0.16	0.20
Direct gross value added in % of sales	37.55	46.85	50.85	51.15	41.35	44.55
thereof direct GVA generated abroad	31.16	34.00	5.11	5.08	9.43	11.67
thereof direct GVA generated in Switzerland	32.22	47.07	71.39	48.66	23.24	27.50
thereof direct GVA generated in the region	36.62	18.93	23.50	46.68	67.33	60.83

588

589 Table 6: Current and future electricity potentials for solar panels [GWh].

Land use	Electricity potential	CH	Emmental	Goms	Surselva	Val de Ruz
2009	LEEP	16,642	79	29	120	35
	Low-conflict ³	15,426	75	21	106	33
Trend	LEEP	20,850	94	37	149	42
	thereof facades	2,224	12	7	27	5
	Low-conflict,	19,386	89	27	132	40
	thereof facades	2,056	11	5	23	5
B2	LEEP	21,457	118	36	150	55
	thereof facades	2,318	15	7	27	6
	Low-conflict,	20,000	113	26	132	52
	thereof facades	2,150	14	5	24	6
A2	LEEP	28,214	182	36	164	115
	thereof facades	3,105	24	7	29	13
	Low-conflict,	26,616	175	26	145	111
	thereof facades	2,919	23	5	26	13

590

³ Low conflict areas always include the categories "no conflict" and "low conflict".

591 Table 7: Current and future electricity potentials from wind turbines [GWh].

Land use	Electricity potential	CH	Emmental	Goms	Surselva	Val de Ruz
2009	LEEP	93,400	1,400	2,300	3,900	1,000
	Low-conflict ⁴	1,235	115	450	430	25
Trend	LEEP	120,000	1,900	3,000	5,000	1,300
	Low-conflict	1,632	215	585	351	85
B2	LEEP	119,900	1,800	3,000	5,000	1,200
	Low-conflict	1,482	195	585	351	26
A2	LEEP	149,900	2,000	3,100	8,500	1,400
	Low-conflict	1,755	215	585	566	91

592

⁴ Low conflict areas always include the categories "no conflict" and "low conflict" of all ES combined. For the four regional studies conflicts with the ES "Aesthetic aspects of landscapes" was not considered since the scale of the underlying indicator data (Table 4) can only be used at the national level. Often the entire region is either included or excluded with no heterogeneity within the selected regions. For reasons of data completeness Figures A1 through A4 (Appendix) include the ES "Aesthetic aspects of landscapes".

593 Table 8: Regional-economic assessment for electricity from solar panels and wind turbines for the
594 four rural study areas in 2035. The electricity potential of the Trend scenario was used [GWh].

Study area and electricity type	Electricity potential [GWh]	Sales 2035 [10 ⁶ CHF]	Gross value added [10 ⁶ CHF]	Regional value added [10 ⁶ CHF]	Regional value-added share [%]
Emmental					
Solar					
LEEP	94	15.0	5.6	2.1	0.19
Low-conflict ⁵	89	14.2	5.5	2.0	0.18
Wind					
LEEP	1,900	361.0	169.1	32.0	2.91
Low-conflict	215	40.9	19.1	3.6	0.33
Goms					
Solar					
LEEP	37	5.9	2.2	0.8	0.38
Low-conflict	27	4.3	1.6	0.6	0.28
Wind					
LEEP	3,000	570.0	267.0	50.6	23.73
Low-conflict	585	111.2	52.1	9.9	4.63
Surselva					
Solar					
LEEP	149	23.8	9.0	3.3	0.34
Low-conflict	132	21.1	7.9	2.9	0.30
Wind					
LEEP	5,000	950.0	445.1	84.3	8.84
Low-conflict	351	66.7	9.0	3.3	0.62
Val de Ruz					
Solar					
LEEP	42	6.7	2.5	0.9	0.31

⁵ Low conflict areas always include the categories "no conflict" and "low conflict" of all ES combined. For the four regional studies conflicts with the ES "Aesthetic aspects of landscapes" was not considered since the scale of the underlying indicator data (Table 4) can only be used at the national level. Often the entire region is either included or excluded with no heterogeneity within the selected regions. For reasons of data completeness Figures A1 through A4 (Appendix) include the ES "Aesthetic aspects of landscapes".

Low-conflict	40	6.4	2.4	0.9	0.29
Wind					
LEEP	1,300	247	115.7	21.9	7.30
Low-conflict	85	16.1	7.5	1.4	0.47

595

596

Fig. 1

a)

b)

598 Fig. 2

599 **Physical solar (s) and wind (w) electric potential (PEP)**

600

601 $PEPs_{x,y} = \text{area of buildings}_{x,y} * \text{solar_radiation}_{x,y}$

602 $PEPw_{x,y} = \text{number of suitable wind turbine sites}_{(\text{windspeed} > 4.5 \text{ m/s})} * 5 \text{ GWh/y (current)}$

603 $* 6.5 \text{ GWh/y (future)}$

604

605 **Electricity potential considering economic and legal factors (LEEP)**

606 $LEEP_{x,y} = \sum_{f=1}^n (f1, f2, f3, \dots, fn)_{x,y} * PEP_{x,y}$

607 $f = \text{economic and legal factors (see Table 1 for solar, Table 2 for wind)}$

608