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# Using the “Footprint” Approach to Examine the Potentials and Impacts of Renewable Energy Sources in the European Alps

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The expansion of renewable energies is regarded as a key way to mitigate global climate change and to ensure the provision of energy in the long term. However, conflicts between these goals and local nature conservation goals are

likely to increase because of the additional space required for renewable energies. This is particularly true for mountainous areas with biodiversity-rich ecosystems. Little effort has been undertaken to systematically compare different renewable energy sources and to examine their environmental impacts using an interdisciplinary approach. This study adapted the concept of the “ecological footprint” to examine the impact on ecosystem services of land use changes involved in exploiting renewable energy sources. This innovative approach made it possible to assess and communicate the potentials of those energy sources in light

of both space consumption and sustainability. The European Alps are an ideal test area because of their high energy potentials and biodiversity-rich ecosystems and the high demand for multiple ecosystem services. Our results demonstrate that energy consumption in the Alps could not be covered with the available renewable energy potentials, despite the utilization of large parts of the Alpine land area and the majority of larger rivers. Therefore, considerable effort must be invested in resolving conflicting priorities between expanding renewable energies and nature conservation, but also in realizing energy-saving measures. To this end, the approach presented here can support decision-making by revealing the energy potentials, space requirements, and environmental impacts of different renewable energy sources.

**Keywords:** Renewable energy; Alps; environment; ecosystem services; space consumption; ecological footprint; Europe.

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## Introduction

The European Union defined the expansion of renewable energies (REs) as a key element in sustainable energy policy and the mitigation of global climate change and greenhouse gas emissions (European Commission 2009; IPCC 2011). Mountainous regions are strategically important because of their high energy potentials and ability to balance fluctuating energy production. However, on the local scale, the expansion of REs generates new conflicts between energy production and nature conservation goals (Jackson 2011). This is particularly true for mountainous areas because of their high biodiversity and increasing land use pressure (Sartoris et al 2012).

REs are not sustainable per se but require a trade-off between carbon-free energy production and local environmental, economic, and social interests

(Evans et al 2009). Common tools to evaluate related impacts and conflicts include the Strategic Environmental Assessment and Environmental Impact Assessment (European Commission 2001). During the last decade, various decision-support systems and recommendations have been developed to analyze trade-offs between carbon-free energy generation and other interests. Most focus on a single energy source such as hydropower (eg Alemu et al 2010), forest biomass (eg Freppaz et al 2004; Frombo et al 2009) or wind energy (eg Voivontas et al 1998; Schillings et al 2012; Regio Energy 2015; Suisse Eole 2015). However, little effort has been made to compare the spatial requirements and impacts of different RE sources in a broader context prior to the planning of specific projects. Until now, this has only been realized in the context of regional energy plans (eg in eastern Germany; Peters et al 2006).

A systematic approach to support decision-making by comparing various RE sources' energy potentials and environmental impacts has yet to be developed. Experience from the Alpine.Space project "recharge.green" underlines the need for new, interdisciplinary concepts to balance the expansion of RE with nature conservation goals (Svadlenak-Gomez et al 2013). Here we examine the potential of a footprint approach to reconcile RE expansion and ecosystem service maintenance with an emphasis on the special situation in mountainous areas. Based on the European Alpine area defined by the Secretariat of the Alpine Convention (2010), this approach is being tested and discussed, aiming to provide a starting point for discussions with decision-makers on conflicts and the spatial scales involved. Furthermore, the presented approach serves as a basis for developing a spatially explicit decision support tool in the Alpine.Space project "recharge.green."

Analyzing RE space requirements is essential, as production rates strongly correlate with space, in contrast to fossil energy (Brücher 2009). Particularly in mountainous areas, the limited availability of space increasingly complicates the expansion of REs. The (human) ecological footprint approach, developed in the 1990s, was successful in communicating the concept of the limited resource "available space" on our planet and the scale of impacts related to human activities (Wackernagel et al 1993; Wackernagel and William 1997). A footprint approach can help to communicate and compare the land demand of different RE sources by calculating the area necessary to provide for the consumption of one person or a group of people. In this context, it is also possible to convey and compare the land requirements of different energy sources (Stöglehner 2003; Zhao et al 2005; Stöglehner and Narodoslawsky 2009).

However, the ecological footprint approach has also been criticized, in particular for not addressing environmental impacts and the sustainability of land use changes (Van den Bergh and Verbruggen 1999; Fiala 2008; Bergh and Grazi 2014). Therefore, we present an approach that incorporates not only spatial constraints, but also constraints related to ecosystem service impacts. In contrast to the ecological footprint approach that focuses on the space required to cover specific resource demands, we focus on energy outputs per defined space unit.

This step is necessary, as little attention has been paid until now to the sustainability of land use change in the context of expanding RE. Particularly in mountainous regions, a broad range of environmental, social, and economic factors constrains the potential of RE sources. The ecosystem services concept has great potential to accommodate this wide range of considerations (Sukhdev et al 2010). Defined as the benefits humans obtain from

ecosystems (Millennium Ecosystem Assessment 2005), ecosystem services are often regarded as a way to measure nature in monetary terms (eg Paletto et al 2015). This approach also provides an interdisciplinary framework to assess the wide range of environmental, social, and economic impacts related to the expansion of RE (Hastik et al 2015) and to approximate a sustainable rate of RE exploitation expressed as "reduced" energy potentials.

In the next step we elucidate the relationship between land cover proportions and energy potentials. To do so, we downscale the total area of the European Alps (191,700 km<sup>2</sup>) to a smaller reference area of 1 km<sup>2</sup>. The linear downscaling of land cover proportions and energy potentials allows us to depict the spatial impact of different RE sources and to compare our results with those from other regions.

## Methods

### The RE "footprint": a stepwise approach

We drew on the terminology of energy potentials provided by Resch et al (2008) to structure a stepwise procedure (Figure 1):

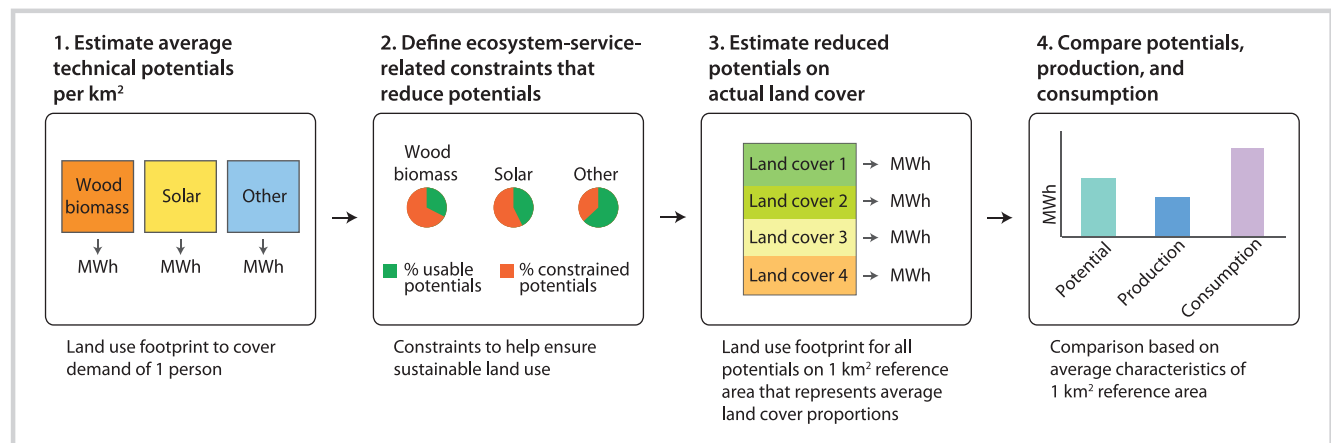
1. Estimate the technical potential of each energy source within the 1-km<sup>2</sup> reference area, taking into consideration theoretical physical energy potentials in the Alps and technical constraints such as conversion efficiency, as described in existing data sets and literature. These technical potentials serve as a basis to evaluate theoretical RE footprints.
2. Define the constraints required to avoid generating negative ecological, social, and economic impacts while exploiting these potentials in the long run, to derive a "reduced potential" value.
3. Correlate potentials and constraints with the land cover proportions of the research area.
4. Reconcile potentials, comparing actual production and consumption based on the reference area and the respective population size.

By comparing the outcomes of steps 3 and 4, decision-makers can capture the difference between actual RE production and demand, estimate land use and ecosystem service impacts if all RE sources are used, and use the information to help balance expansion of RE and other interests such as nature protection.

### Test area and available data

Mountainous areas such as the Alps are particularly affected by expansion of RE because of their fragile ecosystems, high biodiversity, highly appreciated aesthetic and recreational values, and diversity of cultural identities (Hoppichler 2013). At the same time, the Alps are strategically important for the provision of energy for central Europe. The Alpine area defined by the Secretariat of the Alpine Convention (2010) (Figure 2) has

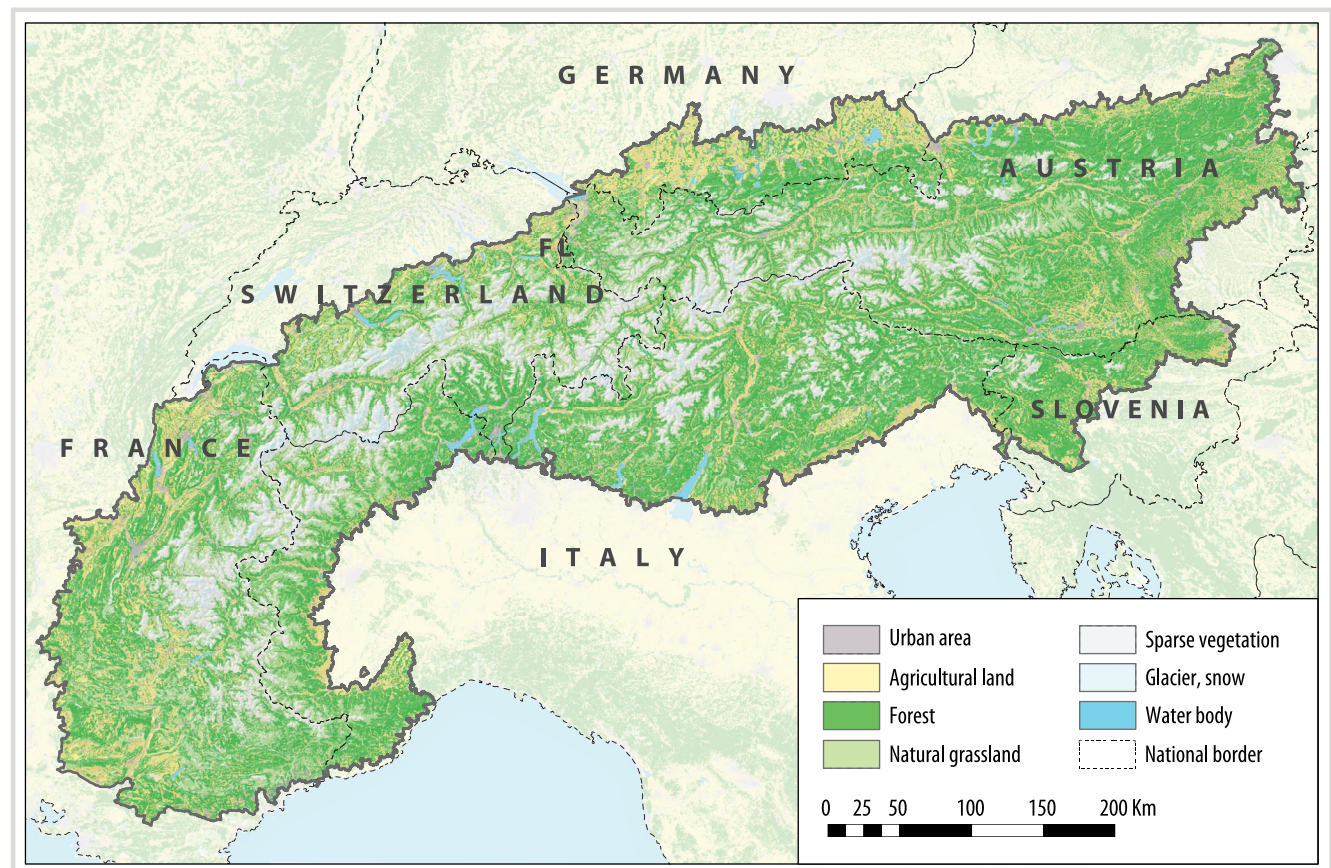


**FIGURE 1** Determining the RE land use footprint.

a size of 191,700 km<sup>2</sup>, includes 8 countries with 14 million inhabitants, and is the holiday destination for approximately 120 million guests per year. Hydropower and forest biomass are traditional energy sources and represent the greatest RE contribution (Haberl et al 2001; Revaz 2001). Other RE sources such as solar energy, wind

energy, biogas, and agricultural biomass are increasingly used (European Renewable Energy Council 2010).

Currently, no literature systematically compares potentials and constraints for different energy sources in the Alps. Therefore, calculations were carried out based on available literature and geostatistical analyses. To do

**FIGURE 2** Land cover in the Alps. (Source: adapted from Hastik et al 2015)

so, we used representative literature sources from individual regions or states, as few existing studies (Garegnani et al 2015) refer to the Alpine area as a whole. Because of the limited literature data available for wind and solar energy, we first calculated these energy potentials for the entire Alpine area (considering the spatial variability) and then downscaled these results for a mean 1-km<sup>2</sup> reference area. Geostatistical calculations were carried out with GIS software (Arcgis, GRASS, QGIS) based on available data sets for the entire area of the Alps (Corine land cover, 30 m digital elevation model). Energy production rates from 2009 to 2014 served as a basis to estimate current energy production rates (*Supplemental material*, Table S1: <http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00071.S1>). In the face of existing data gaps for the Alpine area and related harmonization problems, energy consumption rates were based on statistics available for Austria (Statistik Austria 2014).

## Results

### Estimating average technical potentials per km<sup>2</sup> for the Alps

Forest biomass potentials in the Alps vary strongly depending on soil fertility, climate, and tree species composition. A Swiss forestry inventory (Brändli 2010) indicated yearly stock increment values of 14.7 m<sup>3</sup> ha<sup>-1</sup> under optimal conditions (eg many northern Alpine foothills) and about 5 m<sup>3</sup> ha<sup>-1</sup> in less productive forests (many parts of the southern Alps). An adaption of the International Institute for Applied Systems Analysis global forest growth model (Kindermann et al 2006) indicates a mean annual value of 8.5 m<sup>3</sup> ha<sup>-1</sup> for the Alps. As weight and calorific content vary depending on tree species, we assumed a mean weight of 468.5 kg m<sup>-3</sup> and a mean yearly stock increment of 4.5 kWh kg<sup>-1</sup> based on Hahn (2007).

Hydropower generation generally depends on flow rates and topography. Nevertheless, statistical analyses have shown a correlation between directly impacted (dammed) river length and energy production rates (Schmutz et al 2010). Small hydropower facilities tend to have a larger impact on river courses, per unit of energy produced, than bigger facilities. (Pumped-storage hydropower is not addressed in this article, as its primary aim is to balance fluctuating energy production.)

Wind power potentials mainly depend on wind speed and energy conversion efficiency. Energy yields increase with hub height (higher wind speeds) and rotor diameter (larger harvest area). The footprint can be defined by the harvest area, which is measured in terms of the minimum distance between windmills and the diameter of the rotor (Peters et al 2006). Other footprint references, such as the soil sealed area or the visually impacted area, are not practicable for the Alpine-wide scale of this work. Based on a wind speed map for the Alps at a height of 70 m (Schaffner and Remund 2005) and various ecosystem-service-related

constraints, an average annual wind yield (including at less favorable sites) of 2.2 GWh can be assumed.

Solar energy potentials depend mainly on geographical latitude, climate, topography, and conversion efficiency. For this study we focused on building-mounted photovoltaic units. Therefore, efficiency and performance ratio values were assumed according to current technological standards (European norm EN 15316-4-6). Urban areas in the Alps show a mean solar radiation of 1250 kWh m<sup>-2</sup> or 150 GWh km<sup>-2</sup> electricity output annually, according to geodata provided by the Photovoltaic Geographical Information System project (Šúri et al 2007; Huld et al 2012) and Corine land cover (CLC 2006).

Biogas power plants produce heat, electricity, and/or methane by the anaerobic digestion of manure, slurry, biological waste, and other types of biomass. Large quantities of maize-silage substrate are frequently used because of their high gas yields (Landesumweltanwaltschaften Österreichs 2013). Substrate based on grass silage is less productive in terms of energy output but abundant in many Alpine areas (Amon et al 2005, 2007; Prochnow et al 2009). Biogas energy based on slurry, manure, and organic waste was not analyzed in this study, because of the large uncertainties in the available data.

Comparing the resulting average technical potentials (Table 1) reveals high energy output for solar energy, followed by wind energy (Figure 3). Biomass-based energy sources show much lower values but are nevertheless important to balance energy demand fluctuations. Hydropower potentials per river length strongly depend on local terrain and project characteristics (Schmutz et al 2010); small hydropower plants tend to be less space efficient.

### Defining ecosystem-service-related constraints that reduce potentials

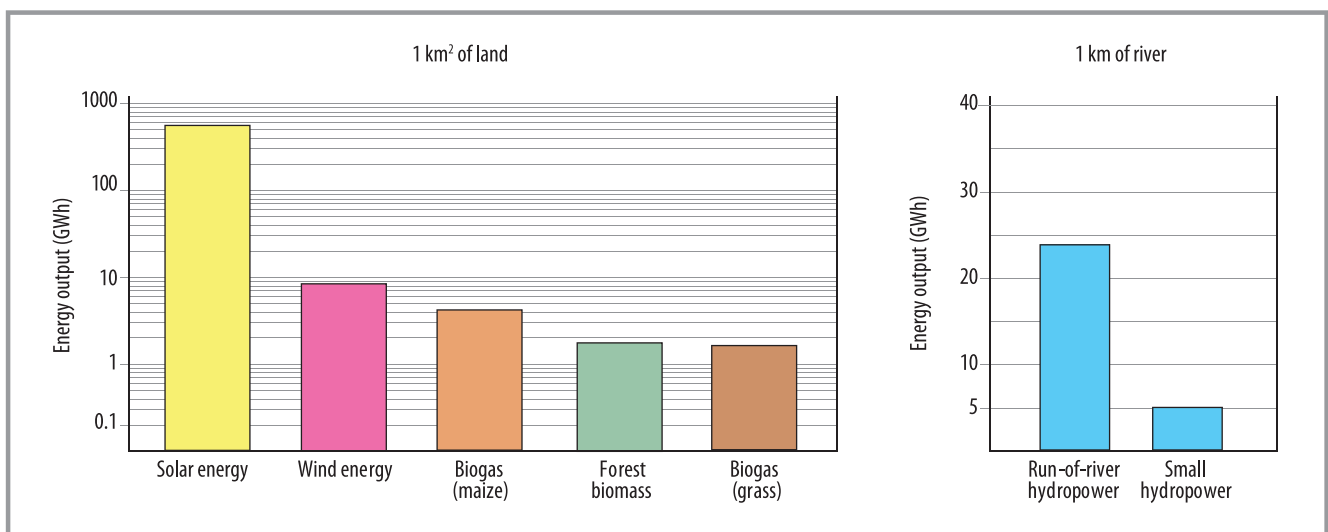
Depending on the RE source, different ecosystem services impacts need to be considered when defining energy use constraints (Table 2). An intensive use of forest biomass might result in a deterioration of biodiversity, for instance due to reduced deadwood levels (Müller and Bütler 2010). Therefore, we assumed a reduced harvest of 70% in protected forest areas, as proposed by Hofer and Altwegg (2007). Besides habitat and biodiversity impacts, increased use of forest biomass for energy generation might result in resource competition with wood-processing industries (Rode et al 2005; Dahlquist and Bundenschuh 2013). As optimized cascaded use can help to reduce resource conflicts, we assumed that half of the industrial wood can be acquired for energy production (Österreichischer Biomasse-Verband 2013). Furthermore, natural hazard protection on steep slopes is regarded as a key function of many Alpine forests, requiring adapted forest management strategies. Data from Switzerland

**TABLE 1** Calculation of the technical potential of RE sources in the Alps (annual values).

Energy source	Technical potential calculations and results	Sources
<b>Forest biomass</b>	Average annual forest growth (g): $8.5 \text{ m}^3 \text{ ha}^{-1}$ Average weight (w): $468.5 \text{ kg m}^{-3}$ Average calorific value (c): $4.5 \text{ kWh kg}^{-1}$	Kindermann et al 2006; Hahn 2007; Hofer and Altwegg 2007; Brändli 2010
	Average technical energy potential = $g \times 100 \times w \times c \times 0.000001$ = $1.8 \text{ GWh km}^{-2}$	
<b>Hydropower</b>	Run-of-river average technical energy potential: $23.8 \text{ GWh km}^{-1}$ Small hydropower average technical energy potential: $5.0 \text{ GWh km}^{-1}$	Schmutz et al 2010
<b>Wind energy</b>	Average yield per windmill (y): $2.2 \text{ GWh}$ Minimum distance between windmills (d): $0.5 \text{ km}$	Schaffner and Remund 2005; Peters et al 2006
	Average technical potential = $y/d^2 = 8.8 \text{ GWh km}^{-2}$	
<b>Solar energy</b>	Average global radiation (r): $1250 \text{ kWh m}^{-2}$ Efficiency (e): 15% Performance ratio (p): 80%	Šúri et al 2007; Huld et al 2012
	Average technical potential = $r \times e \times p = 150.0 \text{ GWh km}^{-2}$	
<b>Biogas</b>	Average maize silage yield (y): $47.5 \text{ t ha}^{-1}$ Maize methane content (m): $93.28 \text{ m}^3 \text{ t}^{-1}$ Average grass silage yield (y): $7.5 \text{ t dry material ha}^{-1}$ Grass methane content (m): $250 \text{ m}^3 \text{ t}^{-1}$ dry material Average calorific value (c): $9.97 \text{ kWh kg}^{-1}$	Amon et al 2005, 2007; Prochnow et al 2009; Fachagentur Nachwachsende Rohstoffe 2013
	Average technical potential (maize) = $y \times m \times c \times 0.9 \times 100 \times 0.000001 = 4.0 \text{ GWh km}^{-2}$ Average technical potential (grass) = $y \times m \times c \times 0.9 \times 100 \times 0.000001 = 1.7 \text{ GWh km}^{-2}$	

show that usage proportions in hazard protection forests vary between 20% and 51% (Hofer and Altwegg 2007). Finally, we assumed that most forest residues are left in place to ensure long-term soil fertility (Katzensteiner and Nemestothy 2007).

Hydroelectric power plants have an impact on aquatic and riverine ecosystems and are likely to hinder migration routes and decrease biological diversity (International Energy Agency 2000; Bunn and Arthington 2002). The recreational value of river courses can

**FIGURE 3** Mean annual RE output in the Alps.

**TABLE 2** Ecosystem services impacts and assumed reductions in potential of selected RE sources.

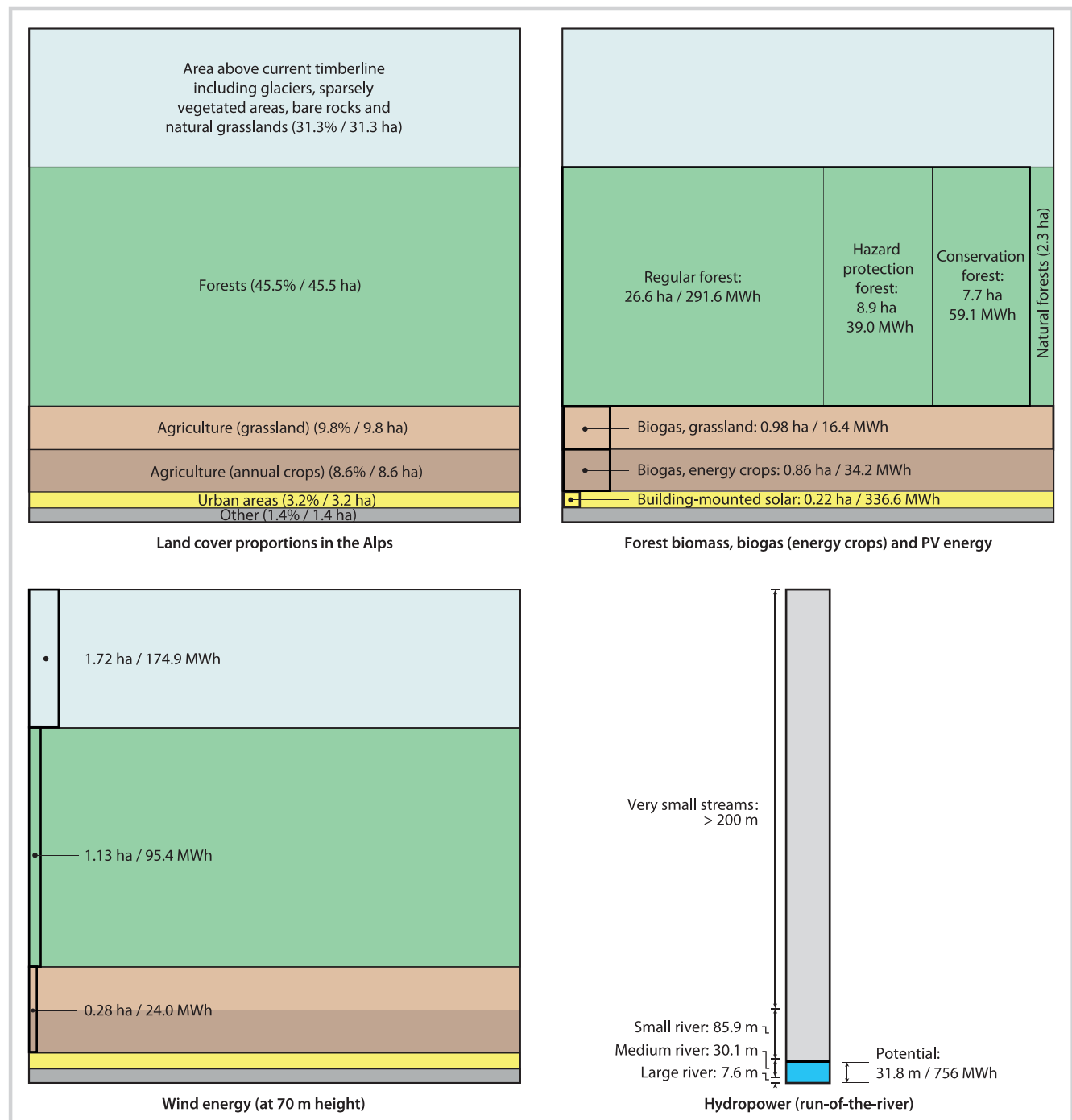
Energy source	Impacted ecosystem services	Assumed reductions in energy potential	Sources
<b>Forest biomass</b>	<ul style="list-style-type: none"> <li>• Natural habitats</li> <li>• Provision of other forest products</li> <li>• Hazard protection</li> <li>• Soil productivity</li> </ul>	<ul style="list-style-type: none"> <li>• Exclusion of protected natural forests; harvest rate reduced by 30% in other protected areas</li> <li>• Limited availability of fuelwood (40%) after wood used for timber and in industry (60%); 50% of industrial wood available for energy generation because of use cascades (residues and waste)</li> <li>• Harvest rate reduced by 40% in forests with important natural hazard protection function</li> <li>• Retention of most harvest residues (13% of total biomass) in forests</li> </ul>	Hofer and Altwegg 2007; Österreichischer Biomasse-Verband 2013
<b>Hydropower</b>	<ul style="list-style-type: none"> <li>• Habitat function of river and adjacent ecosystems</li> <li>• Recreational use of rivers and adjacent areas</li> </ul>	<ul style="list-style-type: none"> <li>• Exclusion of protected and natural river courses</li> <li>• Avoidance of small hydropower</li> </ul>	European Commission 2000; Alpine Convention 2011
<b>Wind energy</b>	<ul style="list-style-type: none"> <li>• Habitat for endangered bird and bat populations</li> <li>• Landscape aesthetics</li> </ul>	<ul style="list-style-type: none"> <li>• Exclusion of nature conservation zones, habitat areas, buffer zones (1 km) for migration routes of endangered bird and bat species, and other protected areas</li> <li>• Minimum distance from settlements (1 km), maximum distance to existing road infrastructure (500 m)</li> <li>• Maximum elevation of 2500 m (to protect pristine high alpine areas)</li> </ul>	Jobert et al 2007; Kunz et al 2007; Regio Energy 2015; Suisse Eole 2015
<b>Solar energy</b>	<ul style="list-style-type: none"> <li>• Provision of food because of a loss of productive land</li> <li>• Provision of raw materials because of loss of potential settlement areas</li> <li>• Landscape aesthetics</li> </ul>	<ul style="list-style-type: none"> <li>• Focus on building-mounted solar energy, limitation of ground-mounted solar energy</li> </ul>	Tsoutsos et al 2005

also be impacted by hydroelectric power plants. Based on the Water Frame Directive (European Commission 2000), we assumed that new hydropower plants cannot be installed in protected river areas and should not degrade existing river courses. We also assumed an avoidance of small hydropower because of its limited potential and substantial ecological impacts (Alpine Convention 2011).

Wind power projects need to consider possible impacts on endangered bird and bat species (Kunz et al 2007). Additionally, windmills alter the scenic beauty of landscapes, and this can influence tourism and people's willingness to accept such projects (Jobert et al 2007). Therefore, we assumed a buffer area around protected areas and settlement areas (BFE et al 2004; Regio Energy 2015; Suisse Eole 2015). Additionally,



**FIGURE 4** Annual RE potentials on a 1-km<sup>2</sup> reference area representing land cover proportions in the Alps. Hydropower potentials are depicted by catchment area-classified river sizes. Mean river lengths are shown for 1 km<sup>2</sup> according to catchment area: very small = <36 km<sup>2</sup>; small = 36–360 km<sup>2</sup>; medium = 360–3600 km<sup>2</sup>; large = >3600 km<sup>2</sup>.



wind energy is avoided in as yet-untouched alpine areas above 2500 m.

Ground-mounted solar energy production competes with the provision of agricultural products and might impact landscape aesthetics (Tsoutsos et al 2005). Therefore, we assumed that most Alpine regions promote

building-mounted solar energy but strongly limit the use of ground-mounted solar units.

An Italian study recently questioned the compatibility of biogas facilities, which depend on intensive agriculture and a large amount of material inputs, with small-scale agriculture in the Alps (Magnani 2012). Therefore, we



**TABLE 3** Annual RE potentials and current production in the total Alpine area (191,700 km<sup>2</sup>) and the 1-km<sup>2</sup> reference area.

Energy source	In total Alpine area		On 1 km <sup>2</sup>	
	Potential <sup>a)</sup>	Current production	Potential <sup>a)</sup>	Current production
Forest biomass	74.7 TWh	70 TWh (94%)	389.7 MWh	365.0 MWh
Hydropower	145 TWh	100 TWh (69%)	756.1 MWh	521.5 MWh
Wind energy	56.4 TWh	4 TWh (7%)	294.3 MWh	20.9 MWh
Solar energy	64.5 TWh	6.5 TWh (10%)	336.6 MWh	33.9 MWh
Biogas	9.7 TWh	No data available	50.7 MWh	No data available

<sup>a)</sup>Potential values represent reduced potential with impact on ecosystem services taken into account.

assumed that 10% of agricultural land could be used for energy crops, in contrast to 20% in some parts of Europe (Hellmann and Verburg 2011). This percentage can be further lowered because of the use of organic byproducts and waste materials.

#### Estimating reduced potentials on actual land cover

Once the technical potentials and related constraints are clarified, it is possible to calculate the footprint of all energy sources within a given spatial unit. Land cover proportions in the Alps based on the Corine land cover data (CLC 2006) were downscaled from 191,700 km<sup>2</sup> to 1 km<sup>2</sup>. For rivers, we first calculated the river length for the entire Alps and then downscaled the river lengths for 1 km<sup>2</sup>. Within forest areas, hazard protection forests (19.5%; Bundesforschungszentrum für Wald 2011) and forests in protected areas (22%; authors' GIS calculations) were distinguished. Furthermore, 5% of the forest area was considered natural forest, without economically motivated forestry activities (Hofer and Altwegg 2007), and 10% of the agricultural land was assumed to contribute to biogas production. The assumption regarding the proportion of buildings in urban areas used for solar energy (13.6%) was based on our own GIS analysis in Tyrol, Austria.

These proportions formed the basis for estimation of the RE footprint using all “reduced” potentials (Figure 4). Energy potentials mapped on land cover proportion, and hydropower potentials depicted by catchment area (Figure 4), show that nearly half of the Alpine land cover and a majority of larger river courses would be dedicated to energy production if all ecosystem-service-reduced potentials were used. In this scenario, forest biomass necessitates the highest land cover percentage (35%). Hydropower offers the highest energy potentials, whereas biomass can be regarded as an important flexible heat source. Solar energy potentials are substantial while impacting only a very small area. Biogas and wind energy could serve as supplementary energy sources. However, potential locations for wind energy projects are mostly limited to areas near and above the timberline.

#### Comparing potentials, production, and consumption

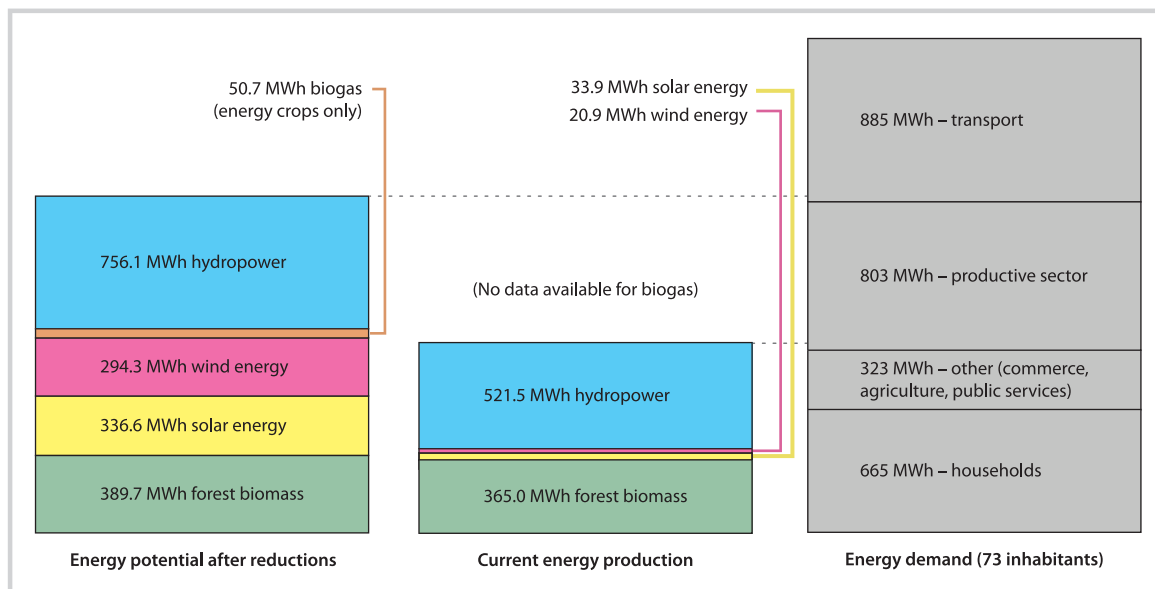
Results for the Alps (Table 3) and the 1-km<sup>2</sup> reference area (Figure 5) indicate that about half of all RE potentials (based on the assumptions made in this study) are currently being used. Most hydropower potential is already realized, whereas substantial potential remains for solar and wind energy. Available forest biomass potentials already seem to be utilized to a large extent, if previously published recommendations (Thees et al 2013) on preserving ecosystem services are to be fulfilled. No data on the use of biogas could be found on an Alpine scale. However, this energy source can be regarded as minor compared to hydropower and forest biomass.

Energy demand rates were based on energy consumption rates per capita in Austria and a mean population density of 73 inhabitants per km<sup>2</sup> in the Alps. A comparison of energy potentials and demands shows that energy consumption exceeds RE potentials by 149%. Therefore, energy self-sufficiency can be reached only by implementing drastic energy-saving measures, even in the Alps.

#### Discussion and conclusion

Comparing energy potentials and current energy production reveals that solar energy has the highest potential for expansion, followed by wind energy and hydropower. In some regions, agricultural biomass could be used as a supplementary energy source. Much like other recent studies from the Alps (eg Hofer and Altwegg 2007; Thees et al 2013), our results suggest that most remaining forest biomass potentials result from underutilization during the last decades. However, this also indicates that any expanded use of biomass resources should be accompanied by energy-saving measures such as improved thermal insulation. In order for the Alps to become self-sufficient in RE, energy demands would need to be reduced and RE production would need to be raised. These goals would be even harder to fulfill if the Alps were to provide RE for central Europe and help supply an increasing demand by the transport sector for vehicles powered by electricity, biodiesel, or biogas (Hartmann and Özdemir 2011).

**FIGURE 5** Annual RE potentials, actual production, and energy demand on a 1-km<sup>2</sup> reference area. (Demand estimates based on consumption data from Statistik Austria 2014)



Land cover proportions depicted in the reference area show that nearly half of the Alpine land cover would be dedicated to energy production if all reduced energy potentials were used. The vast majority of this proportion is related to production of forest biomass, which is likely to cause few conflicts if managed sustainably. In contrast, wind energy is likely to cause conflicts, as most potentials can be found in natural high-Alpine areas as yet scarcely altered by human activities (Pröbstl et al 2011). Remaining hydropower potentials need to be reconciled carefully, as most of the bigger rivers are already intensively used and small hydropower projects tend to impact river ecosystems to a larger extent in relation to the amount of energy generated (Schmutz et al 2010; Platform Water Management in the Alps 2011). Comparing different RE sources revealed a trade-off between low-conflict but land-consuming and controversial but land use-efficient options. To increase the share of RE, a focus on sources with high energy but low conflict potential has been recommended (Sartoris et al 2012). However, particularly in the case of solar energy, problems related to energy storage and other costs need to be evaluated (Palzer and Henning 2014).

In contrast to the basic ecological footprint analysis, the approach described in this article incorporates ecosystem-

service impacts and land use proportions. Therefore, this study makes an important contribution to discussion of the spatial extent and potential conflicts related to RE production. However, the sustainability of human actions such as expanding RE is only conclusively assessable on a local level and within a local context (Volken et al 2011). Because of the scaling involved in the study, and the heterogeneity of the Alps, this approach is not suited to identifying optimal energy production hotspots. As for the ecological footprint approach, problems related to defining system boundaries remain (Van den Bergh and Verbruggen 1999; Fiala 2008; Bergh and Grazi 2014). Nevertheless, these problems are inherent for RE, for instance in defining the size of energy-autonomous regions (Abegg 2011) and dealing with embodied energy that is transferred between regions via trade of goods.

The results of this study highlight the fact that balancing expanding RE and biodiversity conservation is of utmost importance in the Alps. Policy-makers can use this study as an important basis to define further scenarios with diverging assumptions in a GIS-based decision-support system, which is currently being developed in the Alpine.Space project “recharge.green.”

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## Supplemental material

**TABLE S1** References on energy production in the European Alps.

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