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Demonstrating a new framework for the comparison of environmental impacts from small- and large-scale hydropower and wind power projects

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ABSTRACT

Climate change and the needed reductions in the use of fossil fuels call for the development of renewable energy sources. However, renewable energy production, such as hydropower (both small- and large-scale) and wind power have adverse impacts on the local environment by causing reductions in biodiversity and loss of habitats and species. This paper compares the environmental impacts of many small-scale hydropower plants with a few large-scale hydropower projects and one wind power farm, based on the same set of environmental parameters; land occupation, reduction in wilderness areas (INON), visibility and impacts on red-listed species. Our basis for comparison was similar energy volumes produced, without considering the quality of the energy services provided.

The results show that small-scale hydropower performs less favourably in all parameters except land occupation. The land occupation of large hydropower and wind power is in the range of 45–50 m^2/MWh, which is more than two times larger than the small-scale hydropower, where the large land occupation for large hydropower is explained by the extent of the reservoirs. On all the three other parameters small-scale hydropower performs more than two times worse than both large hydropower and wind power. Wind power compares similarly to large-scale hydropower regarding land occupation, much better on the reduction in INON areas, and in the same range regarding red-listed species. Our results demonstrate that the selected four parameters provide a basis for further development of a fair and consistent comparison of impacts between the analysed renewable technologies.

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1. Introduction

Further development of renewable energy sources and the reduction in the consumption of fossil fuels are important elements in the strategy to reduce climate change. As a response to this, the EU has agreed upon the Renewable Energy Sources Directive (EU-RES, 2009). As one of the instruments to meet these objectives Norway and Sweden agreed (from January 1, 2012) on a joint green electricity certificate market aimed at stimulating the production of 26.4 TWh of renewable electricity (Government, 2011). The scheme promotes green energy by offering producers of electricity from renewable sources a green certificate ('subsidy') for every MWh of electricity produced. This is expected to further boost the development of especially small-scale hydropower and wind power in both countries Table 1.

The development of renewable energy sources like hydropower and wind-power is however controversial due to the adverse impacts on the local environment (e.g. Edenhofer et al., 2011; Subramanian, 2012). Within the hydropower sector, there are conflicting views about whether the most environmentally friendly strategy is to develop many small-scale hydropower projects or a few large ones. Despite this, it appears that policies in many countries support the view that 'small is beautiful and large is bad' when it comes to hydropower, and laws and regulations in many countries are designed in such a way that small-scale hydropower

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Table 1
Summary of characteristics of the selected plants/cases for comparison.

Characteristics	Small-scale hydropower	Large-scale hydropower	Wind power
Number of plants	27	1 (3 used for averaging)	1 farm, 48 turbines
Average electricity production (GWh/yr)	350	347 (average)	356
Installed effect (MW)	88.7	76 (average)	150 MW

is given preference over large-scale hydropower (Edenhofer et al., 2011; Koutsoyiannis, 2011), which some authors argue is neither renewable nor sustainable (Frey and Linke, 2002; Koutsoyiannis, 2011). The definition of small-scale hydropower varies substantially from country to country (Frey and Linke, 2002; Edenhofer et al., 2011), as the maximum installed capacity of small hydropower ranges from 1 MW to 100 MW, indicating that the classification is based on political reasons rather than scientific evidence (Frey and Linke, 2002) and is somewhat arbitrary (Egre and Milewski, 2002). In support of this view Gleick (1992) and Edenhofer et al. (2011) argue that differences in installed capacity are not necessarily a good indication of a plant's environmental performance, as smaller facilities might have greater environmental disruption per unit of energy produced than larger units.

Due to the rapid development of new renewable energy production and international commitments there is an urgent management need to have improved methodology for the comparison of the environmental performance of energy projects across technologies (Edenhofer et al., 2011). The following research questions are therefore addressed in this study:

- Can a set of criteria be established that allows the comparison of environmental performance between small-scale hydropower, large-scale hydropower and wind power?
- How valid is it to claim that one type of electricity production has a better (or worse) environmental performance than the other, based on these criteria and the selected dataset of electricity production facilities?

The work in this paper contributes to the fairly limited literature on this field of science. Among the few studies comparing the environmental performance between hydropower (small and large), wind power and other electricity generation options, Evans et al. (2009) concluded that wind power is the most sustainable, followed by hydropower, photovoltaics (solar power) and then geothermal. The parameters used for comparison in this comparison were costs, greenhouse gas emission, availability of sources, efficiency of energy conversion, land requirements, water consumption and social impacts.

Koutsoyiannis (2011) compiled a dataset of 188 existing hydropower projects and found that the occupied reservoir area per unit produced electricity (or installed effect) is smaller for large projects. The study by Kibler and Tullos (2013) evaluated the assumption that many small hydropower projects (<50 MW) is better than a few large hydropower projects based on data from China's Nu River basin. Despite difficulties in finding precise and reliable data they conclude that the biophysical impacts of small-scale hydropower may exceed those of large-scale hydropower projects, particularly with regard to habitat and hydrological change. Kibler and Tullos (2013) used parameters such as habitat loss, catchment connectivity, and priority conservation lands as their basis for comparison. Schmutz et al. (2010) used flooded/inundated river reaches due to hydropower projects as their parameter for comparison and found that 15 reservoir-based hydropower plants came out better than the sum of 803 small-scale hydropower plants, given the same planned energy output (approx. 2.8 TWh).

Bakken et al. (2012) compared the accumulated environmental impacts from 27 small-scale hydropower plants with (the average of) three large-scale hydropower projects in Norway, based on the environmental impact assessments. The results showed a slight tendency for large-scale hydropower to have a lower degree of impacts than many small-scale projects. However, the lack of precision in the data and weak methodological foundation for comparison introduces uncertainty in the results. In a study by Hagen and Erikstad (2013) a number of small hydropower plants in Norway were assessed, and concluded that the impact on local habitats, landscapes and terrain could be comprehensive, and that in order to defend its reputation as an environmentally friendly industry the small-scale hydropower business should take their 'brand mark' more seriously.

2. Method and datasets used for comparison

2.1. Equal volumes of electricity produced

The basis for our comparison of environmental impacts is that the selected technologies should generate similar volumes of electricity (in MWh), without considering other qualities of the energy services provided, such as to what extent the electricity is regulated and the reliability of supply. These are crucial services in an integrated energy system, and the importance of regulating services is expected to increase in the future with a larger share of non-regulated/intermittent sources, such as wind and solar power (Gabrielsen and Grue, 2012). Another commonly used parameter to describe electricity production is installed capacity (in MW) which is the maximum (instant) production a plant or system can deliver, but this does not say anything about the actual production over a longer period.

2.2. Selection of parameters for comparison

Based on methodological problems encountered in e.g. Bakken et al. (2012) an improved approach was developed using a standardized set of indicators enabling direct comparison between electricity production technologies. Parameters in this context are descriptors of specific environmental qualities and they were chosen for their relevance for local environmental impacts, describing both the physical impacts and proxies for biological impacts. The parameters are quantitative in order to allow simple mathematical operations for the purpose of summing, averaging and normalization of impacts. It was also an important criterion that the parameters could be handled uniformly between technologies with as little technology-specific and subjective judgements as possible. The parameters are partly similar to those used in published literature (Edenhofer et al., 2011; Kibler and Tullos, 2013; Evans et al., 2009) and partly defined specifically for our study. Furthermore, the parameters are considered relevant for policy development and implementation (see details in the Sections 2.2.1–2.2.4). The following parameters were selected for comparison:

1. Land occupation (including rivers and lakes/reservoirs)
2. Reduction in wilderness areas (INON)
3. Visibility of power plants
4. Conflicts with red-listed species

One limitation in our study is that all occupied land areas occupied are given the same qualitative value, independent of what

type of nature is occupied, as we have not done any value or vulnerability classifications of the areas.

2.2.1. Land occupation

Changes in land use are by far the largest single cause of biodiversity loss in Norway (Kålås et al., 2010). The protection of biodiversity is governed by the Nature Diversity Act (2009), and state that special care should be paid to land use, land use change and habitat degradation caused by development projects. This is also emphasized in the authorities' guidelines for development of energy projects (OED, 2007). The data on land occupation were obtained by use of data downloaded from 'Norway satellite photos' (www.norgeibilder.no). The occupied areas were digitized manually with use of a Geographical Information System (GIS), in this study the software ArcGIS 10.0 provided by ESRI's (ESRI, 2013).

Areas considered as affected by hydropower (small and large) are those areas occupied by the hydraulic works and infrastructure, typically including the hydropower plants, intakes, outlet structures, penstocks (if not buried), access roads and cleared forest. Also the parts of the watercourses with changed flows, i.e. from the intake in the upper end to the point where the water is released back to the river, are also defined as 'occupied land'. A subjective assessment classified roads as built for the energy project or not. For large-scale hydropower plants, the reservoir areas were defined as occupied land and polygons were drawn around the reservoirs at maximum water level.

For the wind power farms a polygon was drawn outside the outer wind mills based on photos provided by the developer (Statkraft) during the licensing process (www.nve.no), which is also the formal outer delimitation of the facility.

2.2.2. Reduction in wilderness areas (INON)

An important political goal in Norway is the protection of the remaining wilderness areas from human interventions (e.g. Parliament, 2001; Parliament, 2007). The INON-index describes areas with no interventions and was established by the Norwegian Directorate for Nature Management (DN) in order to map the long-term changes in areas free of human interventions. According to the last mapping by DN (2008) energy projects is the single largest cause of reductions in the INON-areas in Norway (DN, 2008). Construction in wilderness areas is for this reason carefully followed in licensing of new energy projects.

The INON areas are defined as those lying at least 1 km in a straight line from the nearest infrastructure object, as defined in the classification manual (Skjeggedal et al., 2005), including roads, power lines, railways and hydropower developments. Following the classification proposed by Skjeggedal et al. (2005) and adopted by DN, buffer sizes of 1 km, 3 km and 5 km are used in this study. Our analysis identifies the INON-areas that are occupied (reductions in INON-areas) due to the energy projects, projected with buffer sizes 1 km, 3 km and 5 km, respectively. Data of INON areas (2008) for this analysis were downloaded from Norway Digital (www.norgedigital.no), converted to a map layer and overlayed with the map data on 'land occupation'. The buffers were calculated from the outer lines of the land occupation polygons.

2.2.3. Visibility of electricity production plants

Recreation in landscapes without any visual disturbances from human interventions is highly appreciated by recreationists and has been a source of conflicts in many energy projects. In the recent debate on the development of grid lines ('monster towers') crossing the scenic Hardangerfjorden (Norway), landscape impacts were not acceptable to several interest groups (Ruud et al., 2011), and caused a very tense conflict with extensive coverage in national media.

In order to calculate the size of the areas where a specific power installation can be seen ('viewshed'), the map layer 'land occupation' was overlayed with a digital elevation model (DEM) with a spatial resolution 5 m was downloaded from Norway Digital (www.statkart.no/Norge_digitalt/Engelsk/About_Norway_Digital/) and processed in a GIS. In our analysis all elements from all technologies were set to 0 m above the terrain. As the rotor-blades at wind farms reaches an altitude of 110 m above the terrain, this assumption would lead to a larger under-estimation of the visibility than for small and large hydropower. Furthermore, it should also be mentioned that due to limitations in the GIS software, the maximum distance the elements could be seen from was 30 km, despite especially wind towers most likely being visible from further away in clear weather conditions, hence under-estimating the visibility areas.

2.2.4. Conflicts with red-listed species

The Norwegian red-list has classified 2398 species as 'threatened' and 1284 as 'almost threatened' (Kålås et al., 2010), and development of small-scale hydropower in steep slopes has a documented effect on rare moss and lichen species (Hassel et al., 2010; Timdal et al., 2010). Both the environmental investigations and the treatment of applications for small-scale hydropower plants put a great emphasis on red-listed species and in particular on red-listed bryophytes and lichens (Evju et al., 2011).

A map layer of red-listed species was based on data from the national species database (Artsdatabanken, 2013). These data were overlayed with a map layer of 'land occupation' (using buffer distance of 2 km and 10 km from the power production sites) to create a conflict map layer. The analysis was carried out under the following assumptions and limitations:

- The locations of threatened species were not diversified with respect of red-list status, i.e. all species observations are treated equally.
- A uniform home-range/mobility of 2 km and 10 km was applied to all threatened species, i.e. species-specific information was not applied in order to relate the buffer to the habitat requirements and distribution range.
- The quality of the basic information in the Artsdatabanken (The Norwegian Biodiversity Information Centre) was assumed to be uniform.
- All observations of red-listed species in the areas are used, independent of whether there might be several of the same species, which would add to the total number of conflicts.

2.3. Description and characteristics of the plants used in the comparison

2.3.1. Wind power plant – Smøla

Smøla wind power plant was selected as the case on wind power production for comparison with small-scale and large-scale hydropower projects (Statkraft, 2013). Smøla is the largest wind power farm in Norway, located in Møre og Romsdal County (Fig. 1) by the west coast in mid-Norway (Fig. 1), producing in average 356 GWh/year. The annual energy production from Smøla was set as the energy base for the total study.

2.3.2. Small-scale hydropower plants

In total 27 small-scale hydropower plants were chosen in order to correspond the energy production from Smøla. All case plants are located in Sogn og Fjordane County (Fig. 1), as the small-scale hydropower development in this county is very extensive, and to ensure comparability with the preceding study by Bakken et al. (2012). The installed capacity of the individual plants was in the

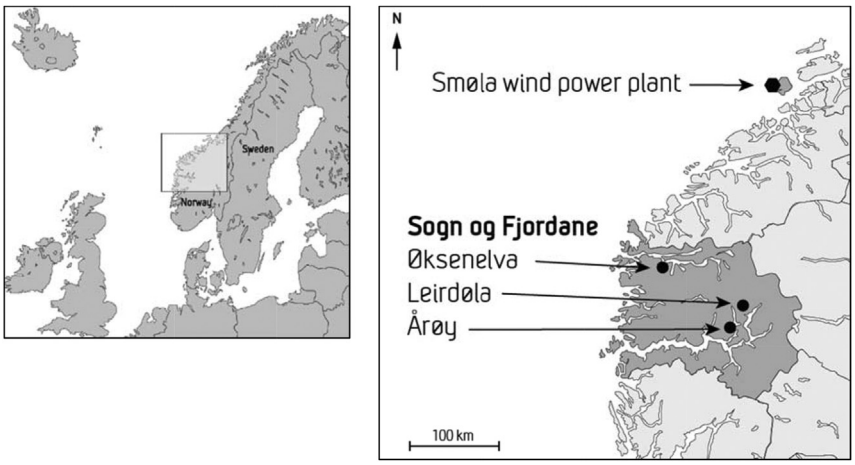


Fig. 1. Map of Northern Europe (to the left) the region of Norway with the exact location of the wind-power plant and the large hydropower plants (to the right). The 27 small-hydropower plants are distributed within Sogn og Fjordane County (grey shade to the right).

range of 1.3–5.3 MW, i.e. within the Norwegian size-classification of small-scale hydropower (>1 MW and <10 MW). The energy production, which might vary from year to year depending on the hydrological conditions, ranged from a predicted minimum of 4.8 GWh/yr up to 24.4 GWh/yr for the largest plant in an average year.

2.3.3. Large-scale hydropower plants

Three large-scale hydropower plants were also selected from Sogn og Fjordane County: Øksenelva (135 GWh/yr), Leidøla (462 GWh/yr) and Årøy (GWh/yr), all reservoir-based plants (Fig. 1).

All the locations used in the study are within the same region in Norway we assume that the biophysical characteristics of the locations are as similar as possible, given the differences in technology. Each technology exploits different types of natural resources, i.e. small-scale hydropower plants will typically be located in steep terrains with small tributaries; wind power plants in open areas exposed to high and constant wind resources.

3. Results and discussion

The annual power production varies slightly between the technologies, and results are presented per unit of produced electricity, i.e. per MWh or GWh. The calculated areas represent what is physically exploited for the purpose of power production.

3.1. The results from the GIS analysis

The summed land occupation from the small-scale hydropower plants is much lower than the average of the large-scale hydropower plants and the wind farm, where the latter two are close to the same (Fig. 2). Looking into the details of the small-scale plants we can see that there are large individual differences. Two of these plants have much higher land occupation per MWh than both the average large and the individual large. Six out of 27 small-scale plants have a land occupation less than 10 m^2/MWh. The average land occupation by the three large-scale hydropower plants is more than twice that of small-scale hydropower. Looking into the details of the large plants, two of the large plants have close to the same area use while the third has almost twice the area use as the two others. The main reason why the large hydropower plants end up with large area use is the size of the reservoirs, which is assigned as 'occupied land'. Related to this, it should be mentioned that the majority of the reservoirs in Norway are established in natural lakes (Hveding, 1992), sometimes with limited changes to the natural condition. Based on our data we can conclude that small-scale hydropower plants produce large volumes of energy in the light of the modest land occupation. If a large run-of-the-river hydropower plant (without reservoir) had been included in the analysis, this would most likely have achieved a 'good score' on this aspect as there are no large reservoirs connected to these types of hydropower plants.

Wind power occupies the same areas as large-scale hydropower projects and much of the area occupation is due to the safety zones around the turbines. The safety zone is set by the authorities as 500 m in all directions because of the risk for the windmill itself or the wings to fall down or the risk of ice-falls from the blades (Holter et al., 2010). There is also a certain distance between the wind mills to avoid aerodynamic disturbance.

The large reduction in INON areas from the small-scale hydropower (Fig. 3) is due to the fact that producing the same volume from many small-scale plants implies several small encroachments in an area, hence fragmenting the landscape. Larger hydropower projects will have more concentrated encroachments, even though the distances from the reservoir, brooklet intakes and access roads can be considerable. In our case, wind power came out by far as the best option with respect to INON. The wind power farm is very concentrated and the single farm selected in our study was situated at a short distance to existing infrastructure (not within an INON area) and hence the park did not cause further effect. As we used only one wind power farm, this result cannot be used to generalize the INON parameter.

The results on visibility (Fig. 4) are unfavourable to small-scale hydropower plants, especially compared to large-scale hydropower and wind power. As the encroachments from the 27 small-scale hydropower plants are distributed over a large area, the results are not surprising. In small-scale hydropower plants most of the infrastructure is located above surface, and even the penstock/pipeline is often visible from the surface despite being buried (Hagen and Erikstad, 2013). This is in contrast with large hydropower, where much of the needed infrastructure is underground, such as tunnels for water transfer, power house and penstock (Hveding, 1992). Furthermore, the majority of the small plants in this study are located in steep fjord landscapes which often can be seen from large areas. There is a large variation in visibility between the individual small-scale hydropower plants, ranging from 70 m^2/MWh to 7399 m^2/MWh. The large hydropower plants range from 32 to

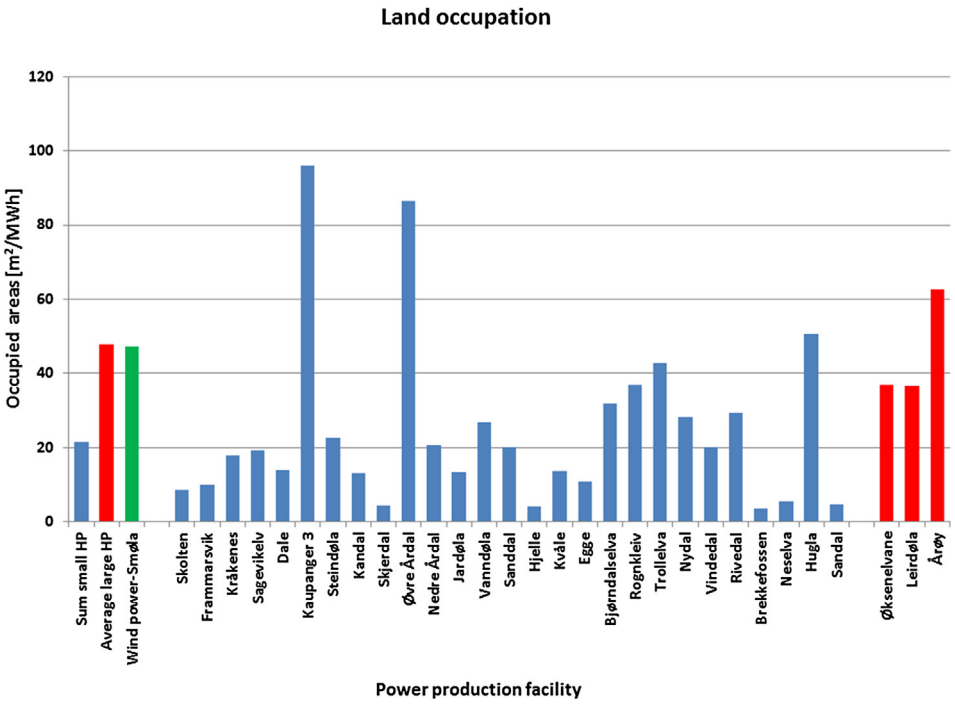


Fig. 2. Land occupation by the studied projects per unit of electricity produced for the three different technologies. The three bars to the left show the aggregate averaged values, the blue bars in the centre present the individual small-scale hydropower plants, while the three red bars to the right are individual results from each of the three large-scale hydropower plants.

34 m^2/MWh as the low estimates to 317 m^2/MWh as the highest of the three large plants in the dataset. As there are only three large-scale hydropower plants in this study, the results are sensitive to the choice of plants in the dataset. The large differences indicates that there can be considerable potential to reduce the conflicts with the respect to visibility (Hagen and Erikstad, 2013; Erikstad et al., 2009).

Wind power plants are often located in open landscape due to wind conditions, and there is great potential for visual disturbances to the landscape, mainly related to the height of the wind mills in the flat landscapes (Strickland et al., 2011). In our analysis all elements from all technologies were set to an altitude of 0 m above the terrain, which also would lead to an under-estimation of visibility, especially for wind power.

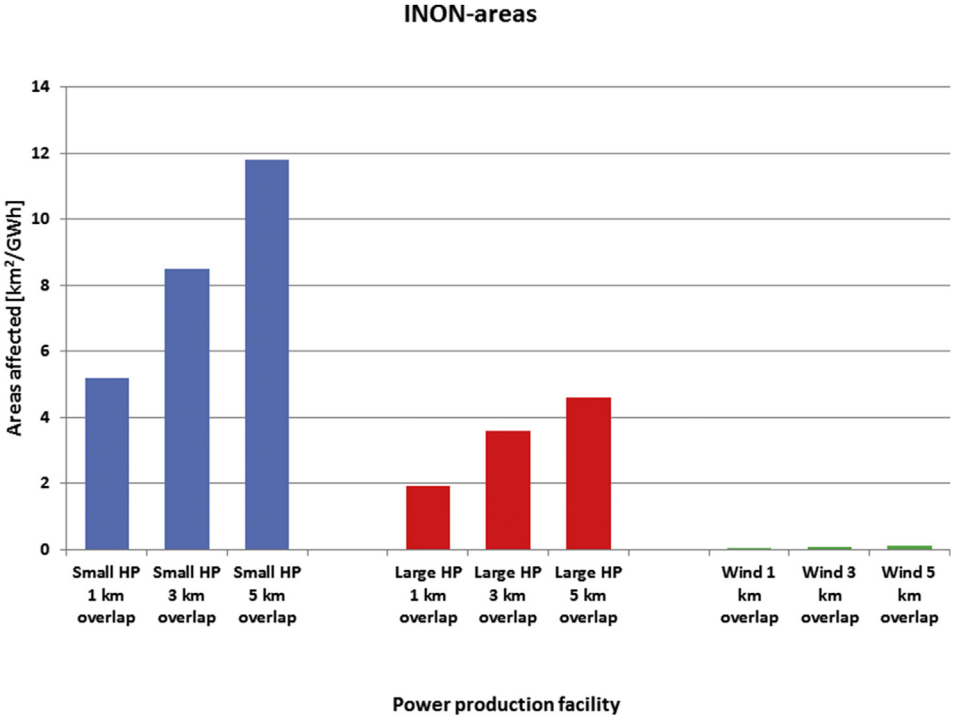


Fig. 3. Reduction in wilderness areas (INON areas) by the analysed energy projects per unit of electricity produced for the three different technologies. The bars present the results with an assignment of 1 km, 3 km and 5 km buffer zones to the project sites, respectively.

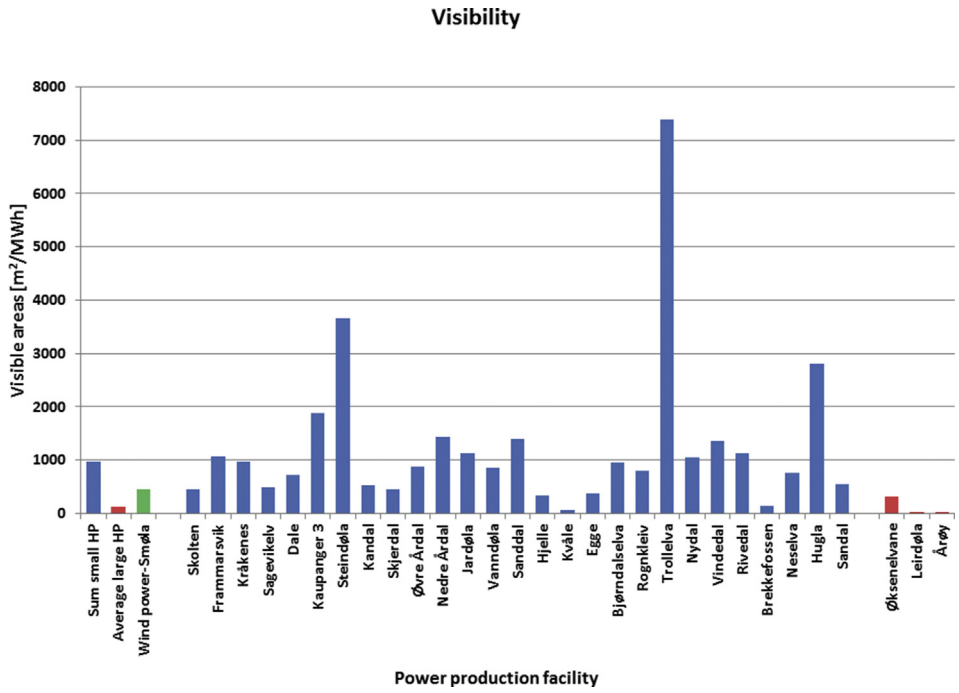


Fig. 4. The figure presents the results from the visibility analyses, i.e. how large areas the energy projects of the three different technologies can be seen from. The three bars to the left show the aggregated/averaged values, the blue bars in the centre present the individual small-scale hydropower plants, while the three red bars to the right are individual results from each of the three large hydropower plants.

Small-scale hydropower plants have the least preferable environmental performance with respect to conflicts with red-listed species in our study (Fig. 5), when assigning both a 2 km and a 10 km buffer zone. The higher conflict level between small-scale plants and red-listed species is likely due to the fragmented nature of development of small-scale power plants. This affects large areas when a buffer is added to many small sites, compared to fewer, larger and more concentrated encroachments in large-scale hydropower plants and wind-plants, even though the direct land occupation is smaller in the small plants.

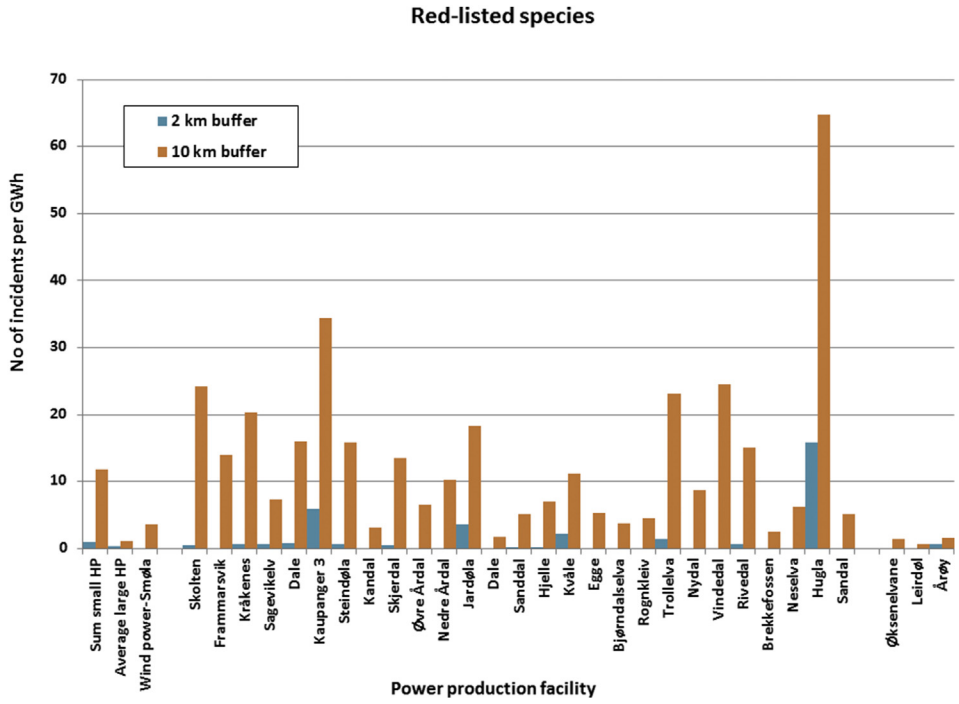


Fig. 5. The number of incidents with conflict between a red-listed species and the selected energy projects, assigning a 2 km (in blue) and 10 km buffer (in light brown) to the energy projects. The bars to the left show the aggregated/averaged values for each of the technologies, the bars in the centre present the individual small-scale hydropower plants, while the bars to the right are individual results from each of the three large hydropower plants.

The analysed large-scale hydropower plants have few conflicts with red-listed species, both when a 2 km and a 10 buffer size are used. The three individual large plants provide a consistent picture with the averaged results. The scores on wind power are also fairly low, especially for the 2 km buffer. Despite the low conflict level for the wind-park in our study the conflict level is high between the presence of sea eagle and the wind power is tense at Smøla, as well as at other wind power sites in Norway (NRK, 2013) and illustrates that other biodiversity values can be worth including as a parameter in a comparison. A major problem with including rare and red-listed species in such studies is the lack of knowledge about species distribution. The environmental assessments are insufficient in mapping of red-listed species, and in particular species from large and important groups as bryophytes, lichens and invertebrates (Gaarder and Melby, 2008; Evju et al., 2011). A review of environmental investigations of small-scale hydropower plants, documented that red-listed lichens were rarely recorded, and red-listed bryophytes were never recorded (Gaarder and Melby, 2008). From this we can interpret that the conflict with red-listed species in our analysis is most likely underestimated. This is even more enhanced in small-scale hydropower plants with a simplified environmental assessment (Korbøl et al., 2009; Jensen et al., 2010), and where the economy is limited to do both doing surveys and study mitigating efforts (Hagen and Erikstad, 2013). The consequence can be that projects with less detailed investigations get awarded as they identify fewer species than those areas that have been thoroughly assessed. A range of habitats can be affected from small-scale plants, but the main focus is gorges and forest (Evju et al., 2011). The diversity of habitats is higher in (not least within) the large-scale hydropower and wind power projects and the potential conflicts might also come out as more diverse.

It is interesting to see from Fig. 6 that there is a trend in the dataset of the small-scale plants that the land occupation per unit of electricity produced is reduced with the volume of electricity produced. The decreased land occupation per volume of electricity produced in the small hydropower plants in our project might imply a general trend that larger small-scale projects (below 10 MW) have a smaller land occupation per unit electricity than the smallest. One explanation can be that larger projects have more resources for technical and environmental competence available. However, this trend does not continue as the large hydropower projects have a much higher land occupation (36–62 m^2/MWh) than the largest small-scale plants (in the range of 5 m^2/MWh). Similar results on the decrease of impact with increased power production (among the small-scale plants) can also be found for the visibility parameter (Aase, 2013).

3.2. Evaluation of the methodological approach

The selected parameters in this study have not previously been used in the context of comparing environmental impacts between energy production technologies. Our experience is that the demonstrated methodology can be a contribution for assessment and a broad evaluation of environmental impact related to energy gain. The quality of the data accessible from public databases is of sufficient quality for the technical analysis, but has some critical limitations for the interpretation of the environmental consequences. This includes limited data for presence/absence of red-listed species (e.g. Hassel et al., 2010; Timdal et al., 2010), insufficient data on related infrastructure such as power lines (Erikstad et al., 2009), and the absence of other environmental attributes (such as habitat qualities, other species, ecological values of connectivity). The selected approach also involves subjective judgements, in the process of digitizing and calculating areas affected by the projects as represented by the calculation of buffers.

Species have very different habitat requirements, so setting a fixed margin to assess influence is problematic. Some species need a large and connected home range (like some birds and fish species, e.g. Helland et al., 2011), while others have very specific and local habitat requirements as presence of dead wood or spurting water (like some bryophytes and lichens, e.g. Evju et al., 2011). At the same time there is a lack of knowledge about species occurrence and environmental vulnerability to the encroachments introduced by the power production projects (Ihlen, 2010). A fixed boundary for the specific sites for the three different production types, call for a standard value on the margin that contains the highest number of actual affected species. If the margin is too large, the calculated number of affected species might be higher than the actual number

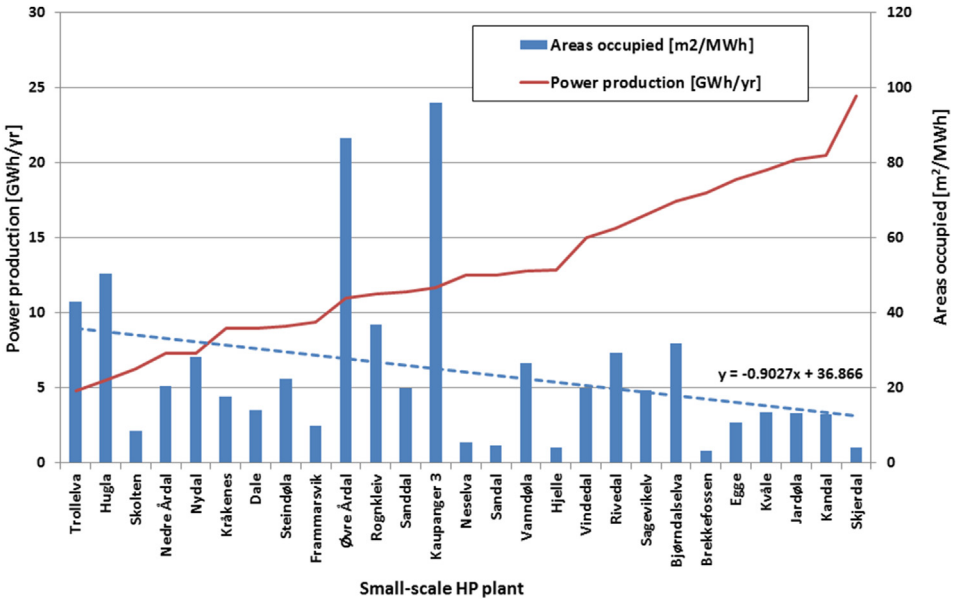


Fig. 6. Small-scale hydropower plants sorted with increasing energy production from left to right and the 'land occupation' per energy volume (the bars). The dotted line represents the linear trend line of the 'land occupation' per energy volume produced, i.e. the land occupation decreases with increasing energy production.

and create bias. But as each site is unique, project areas will affect a high number of species, and some will affect a smaller number. By setting a predefined fixed buffer for each site the results are considered easier to reproduce, despite their limitations.

To omit the transmission lines in this study is another serious limitation that should be improved in a future model. Numerous small-scale plants will need the construction of new infrastructure to transport the electricity onto the central grid. Such transmission lines can cause significant environmental impacts (Bevanger, 1998; Bevanger et al., 2011). The large production sites (wind and the single large hydropower plant) will need high-voltage transmission lines, and a wider landscape corridor than the single small-scale plants, however, smaller power production facilities in total are likely to need longer distances of low voltage lines.

Furthermore, the study does not distinguish between different area types and habitat qualities, i.e. 1 km^2 occupied land is the same as each other km^2 of occupied land. Further studies should include qualitative aspects of the land. The ongoing development of a model for national mapping of landscape types will be very useful for this purpose (Erikstad et al., 2013).

There is a great management need to develop methods for calculating the accumulated impacts from energy projects, as described by for instance Norwegian Nature Diversity Act (paragraph 10) and OED (2007). It is, however, acknowledged by several authors that the methodology is immature (Smit and Spaling, 1995; Canter, 1996; Bakken et al., 2012; Kibler and Tullos, 2013). The calculation of the cumulative environmental impact is a complicated issue, due to the mentioned parameters about quality, connectivity, and lack of environmental data. Improved methods are under development (Erikstad et al., 2009), but in our study we have calculated the accumulated impacts from small-scale hydropower simply by summing the individual impacts for a limited number of parameters, and assuming similar characteristics for all areas.

In our study we compared similar volumes of electricity production based on annual volumes produced. Reservoir-based hydropower is the only large-scale renewable electricity production that provides substantial volumes of regulated electricity production (Edenhofer et al., 2011), and is hence much more valuable to society. This source can provide electricity supply when the hydrological and meteorological conditions do not allow production of electricity from small-scale plants or from wind power and can 'fill in' in periods where peak power production is needed. An interpretation of the results can be that society has to 'sacrifice' nature resources in order to provide this type of service ('battery service').

3.3. Policy

In the management of energy and environmental resources and there is a difficult and delicate balance between political goals for more renewable production on the one hand (EU-RES, 2009) and achieving certain environmental standards and the protection of nature on the other (OJEC, 2000). Reconciling these aspects is difficult. It needs explicit priorities and should not be left to case-by-case management. The recent agreement on the el-certificate market between Norway and Sweden (Government, 2011) might speed up the development of new energy projects, and put additional pressures on remaining resources. A more open and precise discussion is needed as different political priorities will lead to different management practice. Based exclusively on our results, the policy formulation will be determined by the weights that are given to each of the analysed parameters. If the highest priority is to stop reduction in INON areas the massive development of small-scale hydropower should be reduced, but if the land occupation is the single-most important environmental parameter to minimize, small-scale hydropower development is more favourable, according to our study.

The concept of ecosystem services assessment (ESA) (Kumar, 2010) is now under consideration for a wider application in the management of waters in Europe (EU, 2013). ESA opens up for offsetting of habitats, but it has been identified as a methodological challenge to define habitat equivalency and similar user interests, which is needed in order to carry out compensation and offsetting the impacts of different projects across ecosystem services. Our work might provide a platform for offsetting impacts between different types of electricity production. An assumption is that areas that are degraded due to energy projects (or other means) can be compensated with similar-sized or similar-quality areas elsewhere (Moilanen et al., 2009; Quigley and Harper, 2006). This is a very crude assumption and quality aspects (e.g. via nature types) of the occupied areas should be introduced, for instance by classifying the areas by nature type (Bruggeman et al., 2005). Assuming also that a ratio could be established between the nature types, offsetting could also be supported between energy projects of different technologies, but this topic certainly needs further work. Crucially, the ecosystem services approach acknowledges that different locations can have different user interests and hence different values even when physical characteristics may be similar.

4. Conclusions

Introducing the parameters of land occupation, reduction in wilderness areas (INON), visibility and impacts on red-listed species is one promising way forward to compare environmental performance between electricity-producing technologies. These parameters provide a common and quantitative basis with the same dimensions and units, allowing direct comparison between technologies. In this study small-scale hydropower scores best on the parameter of land occupation, i.e. uses the smallest land area in order to produce the same volume of electricity as large hydropower and wind power. Wind power comes out similarly to large-scale hydropower regarding land occupation, and much better on reduction in INON areas. Both wind power and large-scale hydropower perform better than small-scale hydropower with respect to red-listed species. As such, the study is in line with the findings of Bakken et al. (2012), Edenhofer et al., (2011) and Kibler and Tullos (2013), bearing in mind that these comparative studies were based on other environmental parameters. There are, however, large individual differences between the single energy plants (small- and large-scale hydropower) indicating that there is a potential to reduce the negative environmental impact with careful siting and mitigation efforts.

The selected parameters in our study do not cover all the environmental impacts of energy projects as these parameters are not proxies for all physical and biological qualities of the natural environment. It should also be noted that our results do not diversify the impacts within one and the same environmental parameter as the qualities of the areas are treated uniformly. This is a critical shortcoming with regards to an ecosystem services dimension in our results. Further research should focus on including the quality of the areas affected by the energy projects, including related infrastructure, ensuring a consistent and fair mapping between technologies, and also including a larger set of parameters describing the quality of the energy services provided. As a regulated and reliable supply of energy has a higher value to society, our simple comparison based on similar volumes of energy based on annual production does not take into account the benefits of reservoir-based hydropower.

Policy objectives should be expressed more precisely when it comes to trade-offs between the development of new energy

sources and protection of the environment. All renewable energy projects will have some negative impact on environmental qualities, and minimizing and mitigating these effects is of relevance to society. One type of technology can be less damaging with respect to impacts on red-listed species while another technology might be the better choice in order to avoid further reduction in INON areas. The potential for mitigation and offsetting of impacts can also vary between technologies. Today's practice in Norway is that a project developer applies for a specific project at a specific site, and the authorities say yes or no to the proposed project, possibly with some restrictions. This can lead to sub-optimization of resource use and environmental impacts, possibly also within one technology. It is pertinent to ask whether a better strategy would be for the authorities to call for bids for the 'best electricity project independent of technology' within a region, given that a certain volume of electricity of a specific quality needs to be developed.

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