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A SOLAR ATLAS FOR BUILDING-INTEGRATED PHOTOVOLTAIC ELECTRICITY RESOURCE ASSESSMENT

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ABSTRACT

While photovoltaic energy gathers momentum as power costs increase and panel costs decrease, the total technical and economic potentials for building integrated solar energy in Denmark remain largely unidentified. The current net metering feed-in scheme is restricted to 6kW plant size, limiting large scale application. This paper presents a solar atlas based on a high-resolution digital elevation model (DEM) of all 2.9 million buildings in the country, combined with a building register. The 1.6 m resolution DEM has been processed into global radiation input, solar energy output and production costs for roof areas of individual buildings. Size of roof areas is included for a technology assessment and a quantitative stakeholder analysis. The resulting costs of supplying up to 40 TWh of electricity annually have been calculated by means of levelised production costs at various interest rates. The continuous assessment of solar electricity generation potentials by marginal costs, ownership and plant type presented in the paper may be used for defining long term policies for the development of photovoltaic energy, as well as political instruments such as a multi-tier feed-in tariff.

Keywords: Photovoltaic electricity, resource economy, feed-in tariff, GIS

1 INTRODUCTION

Solar photovoltaic (PV) electricity is a technology in rapid growth thanks to support mechanisms such as feed-in tariffs, which secure a fixed payment per unit of electricity delivered to the public grid[1,2]. The establishment and maintenance of such support mechanisms require a solid overview of the potentials and costs of energy production in order to secure efficiency and equity.

Building integrated solar power using photovoltaic panels makes use of existing support frameworks and grid infrastructure in buildings and reduces the footprint of area-intensive utilization of solar radiation. There is a good spatial correlation between the electricity consumption of buildings and their generation potential, particularly for single family homes and industrial buildings[3].

Compared to the global leader in PV Germany, Denmark is not currently utilizing much of its solar energy potential. Although its insolation is about the same or higher than Germany, the small Scandinavian country is more known for its use of wind energy[4]. The recent reductions in PV investment costs, a net metering scheme combined with taxation of electricity, as well as a tax credit on PV installations have led to an annual growth of up to 60 % since 2010[5]. Currently there are 5069 plants installed with a total capacity of 22 MW. Studies carried out on the future Danish energy system, which is to be based on 100 % renewable energy in 2050, have suggested at least 5 GW PV may be realistic to incorporate into a future system[6].

There are about 2.9 mio buildings with a total footprint area of roughly 600 mio. m^2. Assuming 120 W/m^2 peak power density and a utilization rate of a third of the footprint area as theoretically available roof area, the theoretical potential is in the magnitude of 20 GW. The economic potential is hypothesized to be much lower, depending on actual roof insolation and roof suitability and the level of feed-in tariffs or other support mechanisms[7]. It is therefore relevant to establish a relation between the available PV potential and its generation costs. Furthermore, it is important to enquire about the size of coherent roof areas, type of buildings, as well as the geographical location: there is an economy of scale that favors larger plants [8]; at the same time the current net metering scheme is limited to 6 kW installed peak power. Ownership of buildings has consequences for types of PV plant ownership and operation, while the geographical location is of interest for e.g. municipalities, which like to know their local potential of PV as part of their strategic energy planning, see [9-11].

Several examples of municipal solar atlases have been developed in the recent past, such as the German SunArea [12] or the Bristol Solar Map [13]. For Denmark no such method exists, which can help assessing the use of PV at larger scales by means of quantitative data on potentials as well as their associated costs. A tool is needed for the energy-political evaluation of support mechanisms, which facilitates the analysis of cumulative feasibility. Such a tool must be available for larger geographical areas like regions or the whole country and handle extensive input data. The aim of this paper is to develop a solar atlas with these characteristics.

2 MATERIALS AND METHODS

A relation between the potentials and costs can be established by mapping the annual power production for an entity of roof area, for which the costs of production can be calculated as the levelised production costs (LPC). LPC assume a net present value of zero after ended useful lifetime, or an internal rate of return equal to the interest rate. Power production of a PV plant is a function of the global irradiation at a location, the orientation and inclination of a PV panel as well as the size and type of systems. Size- and type specific efficiencies and losses are to be applied. The production costs are a function of power generated per area, the investment per area, as well as the operation and maintenance costs. Global parameters are the interest rate and the lifespan of the PV plant. The next step is the combination of production and costs to a supply curve, where the marginal costs of generation are drawn over the cumulative potential production. The supply curve allows identifying the potential generation, which has costs below the power purchase costs (for net metering) or the feed-in tariff. It is possible to generate supply curves by area (for a municipality e.g.), by type of plant (e.g. size) or by ownership of the building. Comparing different supply curves for given discount rates or technical parameters, the economic potential for each instance can be found.

It is pertinent to find the roof areas available as well as their annual global radiation, which is a function of geographical location, inclination and orientation of a given roof area as well as possible shadowing from surrounding elevated objects[7,14]. The main input to the model is hence an elevation model of such precision and detail, that it allows calculating these parameters for each roof or for finite elements of roofs. The Danish Cadastral and Mapping Agency KMS has developed a new digital elevation model (DEM) based on LIDaR (Light Detection And Ranging), which contains ground elevation as well as the elevation of objects such as buildings, trees etc[15]. Its geographical resolution is 1.6 m, equal to a grid cell size of 2.56 m^2. With such a detailed elevation model it is possible to calculate orientation, inclination and shadowing for individual parts of roofs, as even roofs of small buildings are composed of 50 or so individual pixels. This type of data has been used successfully in several countries so far [16,17] and hypothetically it allows for mapping of the building integrated solar power production for all Danish buildings in unprecedented detail.

2.1 Extraction of a building-sharp elevation model

The DEM with surface (DSM) and terrain (DTM) elevation models is available through an FTP-service from KMS, where the about 600 individual DSMs and DTMs can be downloaded for the whole country in 10 x 10 km tiles in ASCII-grid format. Processing of this data happens in ArcGIS 10 with Spatial Analyst, where the ASCII grids are imported to ESRI grid format and extracted to the outline of buildings from a high resolution digital vector map called FOT-Kort10, resulting in a grid, which includes the elevation of individual buildings. This building elevation model (BEM) is the input to a solar irradiation calculator included in ArcGIS Spatial Analyst, which returns the annual radiation values summarizing half-hour intervals and using given proportions of direct and diffuse radiation. Shadowing caused by other buildings is included, while shadows from other objects, like trees, are not included because of data size limitations of the solar area tool. Two main shortcomings of the data model are that roof areas are not depicted with their true geometry but as coarse pixels, and that the interpolation from LIDaR point data has led to blurred, curved and noisy roof areas. Access to the original LIDaR data would have yielded better results, but at the costs of processing time [18] as well as high costs of data purchase.

2.2 Calculation of photovoltaic electricity production

To calculate the global radiation on roof areas the ArcGIS Solar Area tool has been used, which generates upward-looking viewsheds for every location of a DEM in order to calculate insolation. The resulting insolation maps are deemed accurate for high-resolution DEMs [19]. Once the global radiation is known for all roof areas, the annual power production is calculated applying system efficiencies for typical PV plants on the market. Efficiencies are a function of plant size and technology (poly-, single-cristalline etc). Based on experiences in Denmark [20] and calculations using empirical data [7,21] an average efficiency of 11% was derived. While larger plants usually have more efficient inverters, their cable losses reduce scale effect to less significance. The useful roof area is in many cases restricted by technical installations, bay windows and hatches. A survey of typical buildings comparing the elevation model with orthophotos has shown that about 80% of the roof area is available for PV installations.

2.3 Determination of plant type and size

Plant size determines the specific investment costs, which decrease for larger installations. To determine plant size, coherent roof areas are found from the DEM by grouping then into regions using a four neighbour rule[22]. The geometric area of coherent roof areas was then calculated and made subject to a classification into plants of different size, see table 1:

Table 1. Main technical and economic parameters of PV plants used in the study. Optimal production data are for a global radiation of 1,000 kWh/m2/a, an orientation of 180 degrees (due South) and an inclination of 45 degrees.

Area	**spec. inst. cap.**	**spec. investment**	**spec. investment**	**spec. production, optimal**
m2	**kWp/m2**	**€/m2**	**€/kWp**	**kWh/m2**
<20	0.1210	351	2,899	112
20-50	0.1232	305	2,479	114
50-200	0.1243	254	2,047	115
200-4000	0.1250	218	1,744	115
>4000	0.1270	200	1,575	116

PV plants on flat roofs can be mounted horizontally or at optimal inclination. Horizontal mounting reduces panel output, while mounting at optimal inclination reduces panel size but also total panel area. In a northern country like Denmark the necessary horizontal distance between rows of panels reduces useful panel area by about 50%, while the higher diffuse radiation leads to lower reduction of horizontal panel output of 10-15%. Therefore in all cases panel inclination and orientation follows the actual roof surface from the DEM. Operation and maintenance costs are set to be 1% of the investment per year.

2.4 Calculation of levelised production costs

The costs of power production are calculated as the levelised production costs (LPC), which express the average cost of generating one unit of electricity during the useful lifetime, including annualised investment costs:

$$LPC = \frac{I}{aE} + \frac{om}{E} \qquad (1)$$

Where *I* is the total investment (solar panels, wiring, inverter and installation costs) in €, *om* the operation and maintenance costs [€/MWh], *E* the annual power production [MWh] and a the annuity factor:

$$a = \frac{1-(1+r)^{-n}}{r} \qquad (2)$$

with *n* being the useful lifetime in years (25 years are assumed) and *r* the interest rate, which is either 3% or 8%. LPC are calculated for each grid cell of 2.56 m^2, hence a roof with different global radiation, partly shadowing or variable azimuth or inclination will have individual costs for each part.

3 RESULTS

For technical reasons and computation times longer than expected the full set of results for 97 Danish municipalities could not be incorporated in this version of the manuscript. The authors need a couple of weeks more to solve these problems and will present the results for the whole country on the conference and in a later version of this paper. Instead, the solar atlas presented here includes the municipality of Aalborg as well as most of the greater Copenhagen area. These two areas are representative in size and urban structure for the rest of the country. The computational effort is the maximum of what can be achieved with the current software version.

3.1 Total PV potential by plant size

Five different plant sizes were included, see table 1, which represent small scale applications, installations on single- and on multifamily homes, as well as larger installations on industrial or public buildings. Areas with an insolation smaller than 600 kWh/a were excluded. The total technical potential using all available roof area is 4,526 GWh/a in Aalborg and 8,642 GWh/a in greater Copenhagen. Medium sized plants of 200 – 4000 m2 comprise by far the greatest part of the technical potentials, followed by plants of 50 – 200 m2.

Table 2. Total technical potentials exceeding 600kWh/m2/a insolation for PV in Greater Copenhagen and in Aalborg Municipality by plant type.

Greater Copenhagen:			
Plant type	Total area [m2]	Average insolation [kWh/m2/a]	Total PV production [MWh/a]
20-50m2	743,831	776	225,425
50-200m2	6,418,100	786	1,971,290
200-4000m2	15,162,800	781	4,628,640
>4000m2	5,959,100	780	1,816,570
Aalborg municipality:			
Plant type	Total area [m2]	Average insolation [kWh/m2/a]	Total PV production [MWh/a]
20-50m2	477,519	753	140,521
50-200m2	4,281,740	759	1,269,340
200-4000m2	8,713,050	757	2,575,530
>4000m2	1,831,920	755	540,362

3.2 Cumulative PV potential by marginal costs of production

For a discussion of future feed-in tariffs it is relevant to ask which level of subsidisation such a tariff should comprise. As we can see from fig X, the LPC of PV plants increases with the cumulative supply. The amount of economically feasible power production is limited by the constraints of current efficiencies, costs as well as the availability of roof areas with favourable geometry.

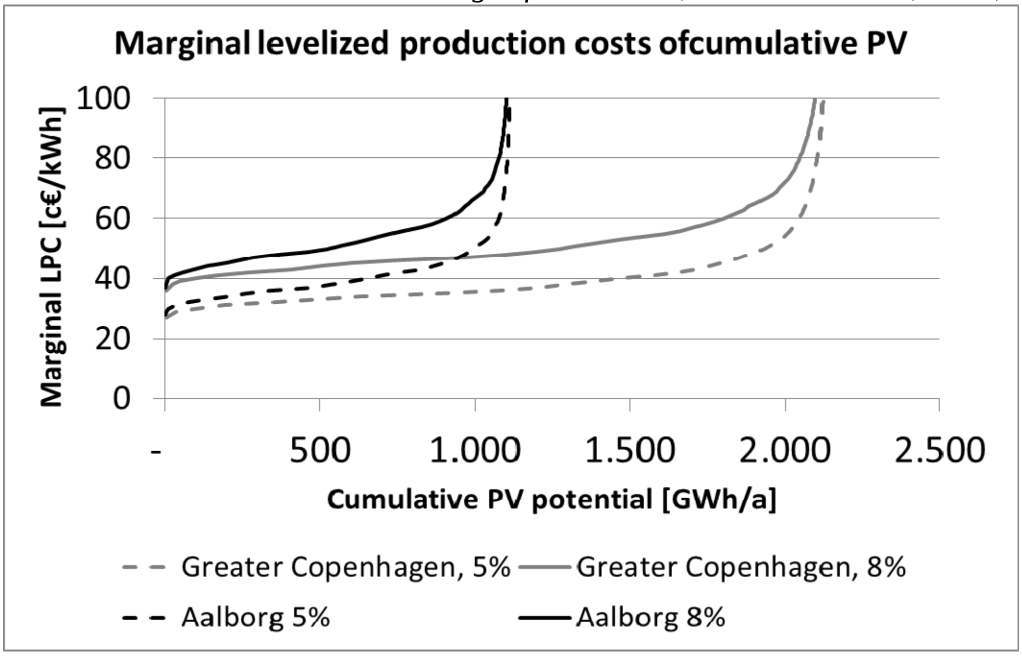

Figure 2: Marginal levelised production costs of cumulative PV for Greater Copenhagen and for Aalborg municipality at 5% and 8% interest rate.

3.3 Economic PV potential for types of installations

A main aspect of designing feed-in tariffs of other support mechanisms is the attention to which types of plants will gain the most of these schemes. Larger plants have lover generation costs, but their type of ownership may require higher rates of return. Cost-supply curves therefore can be used to propose levels of feed-in tariffs. Respective of the two areas calculated so far it can be seen that, assuming a low interest rate of 5%, the current net metering scheme with its equivalent of 30 c€/kWh allows for the compensation of about 10% of the potential in Greater Copenhagen, whereas the insolation in Aalborg is not quite sufficient to return any investments at this rate. Going from 5% to 8% interest rate at an fictional feed-in tariff of 40c€/kWh reduces the feasible potential by about 90% in Copenhagen and even more in Aalborg. This is because a large proportion of the cumulative potential is within a rather narrow cost band.

4 CONCLUSIONS

A national geographical model of roof-based photovoltaic electricity production potential and costs has been developed, based on high-resolution DEM and a generic solar radiation algorithm based on upward-looking viewsheds. For each building in Denmark the PV potential and the levelised costs of power generation can be calculated for different plant types by size and using different interest rates. Preliminary results have been presented using cost-supply curves, which show the marginal production costs for the cumulative generation potential. These curves have been used to establish a geographically specific link between the PV resource and its costs, which allows for distinguishing between the technical and the economic potential under various constraints.

Two innovations are imminent in the present study. First, the data used is generic and available from public mapping authorities in many countries. If small errors due to the poorer representation of roof geometry compared to methods using LIDaR data directly are acceptable, the use of raster-based DEM allows for faster and cheaper models. The second innovation is the continuous calculation of resources and their associated costs, which allow for a resource-economic assessment of the PV potential present in a geographical area, a selection of plant types by ownership, or a given technology.

The use of raster data available from public bodies mean that municipalities and research institutions have free access to what otherwise comprises a considerable cost. Being able to continuously assess the costs of utilising a geographically distributed resource is a great aid in deciding on a feed-in tariff and for evaluating its effect.

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