

Assessment of spatial implications of photovoltaics deployment policies in the Netherlands

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ARTICLE INFO

Keywords:

Solar-PV

Spatial assessment

Policy choices

PV potential

Land use classification

ABSTRACT

Electricity generation with photovoltaic (PV) solar energy technology requires significant amounts of space; a particular point of discussion in a densely populated country like the Netherlands. Therefore, we developed a new analytical framework to analyse potential electricity generation for specific PV typologies on 43 different land utilisation and water types. Our results indicate that spatial potentials for PV are substantial compared to current Dutch scenarios and ambitions for its role in a long-term decarbonised energy economy. The spatial potential of PV on rooftop areas is sufficient to largely meet these ambitions; however spatial allocation depends on more factors than the potential alone, e.g. desired implementation speed. Therefore, we have sketched some variants with a more balanced allocation over the various land use types. Innovative options, such as PV within offshore wind parks and on infrastructure, parking spaces and façades offer considerable opportunities for additional generation. Furthermore, we illustrate the considerable impacts on PV potential of (i) current net metering policy, (ii) the upcoming societal preference for lower panel densities in land-based PV parks, and (iii) a focus on cost efficiency instead of spatial efficiency. Policy makers should bear these outcomes in mind when designing support schemes for PV.

1. Introduction

Photovoltaic solar electricity (PV) is generally considered an important element of our future decarbonised energy economy, next to a manifold of other technologies (IEA, 2020a; IPCC, 2011; IRENA, 2020, 2018; Shell, 2018). Today, PV power generation capacity is growing strongly throughout the world (Frankfurt School et al., 2020; IEA, 2020b), reaching up to 760 GW_p by the end of 2020 (IEA-PVPS, 2021). Both observations also hold for the Netherlands: While PV accounted for less than 5 % of total electricity production in 2019 (CBS, 2020), future climate-neutral scenarios project that PV could generate up to one third of total electricity demand in 2050 (Den Ouden et al., 2020), which due to electrification of energy demand is projected to increase two- or threefold (Den Ouden et al., 2020; Scheepers et al., 2020). PV

deployment in the Netherlands has been showing an average 50 % annual growth rate for more than 10 years now (CBS, 2020), reaching up to 10 GW_p capacity by the end of 2020 (CBS, 2021); double-digit growth is expected to continue in the next decade (PBL et al., 2020).

However, PV systems require space, which is a particular point of discussion in a densely populated country such as the Netherlands (Kuijers et al., 2018; Londo and Kramer, 2019; Sijmons, 2008; Uytendinck et al., 2017). Several studies have reviewed PV potentials on various area types in this country (Anonymous, 2018; Defaix et al., 2012; Druten and Kruit, 2019; Folkert and Wijngaart, 2012; Folkerts et al., 2017; Jager et al., 2017; Lemmens et al., 2014; Quintel Intelligence, 2020; Sijmons et al., 2017; Veenstra, 2015). These studies generally focused on rooftops, and only some of them also considered other land utilisation and water types (LUWTs) such as infrastructure,

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terrains, and water in a relatively simplified manner. The absence of a more detailed estimate of potentials on all LUWTs is a relevant shortcoming because today, we see significant growth of PV systems in the Netherlands on rooftops as well as on agricultural lands and surface water (RVO, 2021). Moreover, this development generates wide societal debate on the desired PV deployment balance between the various LUWTs. Although more generic GIS (Geographic Information System)-based potential studies exist (Guaita-Pradas et al., 2019; Perpiña Castillo et al., 2016), a comprehensive and bottom-up estimate of such potentials on all kinds of land utilisation and water types (LUWTs) in the Netherlands is still missing, as well as an analytical framework that shows the impact of choices in application of PV on different LUWTs.

Therefore, this study aims to estimate the spatial potentials for PV on all types of land use and water in the Netherlands. We also explore the spatial implications of several possible policy choices and preferences and show how these relate to the future ambitions for PV in the Netherlands.

2. Methodology

Assessments of potential renewable technology deployment usually apply terms such as physical, spatial, technical and economic potentials (Dupont et al., 2020; Gernaat et al., 2020; Hoogwijk, 2004; Mavsar et al., 2019; Ruiz et al., 2019). In this study, we focus on the spatial potential, given physical (e.g. solar irradiation) and technical constraints. Spatial considerations that have technical implications were considered as well, by defining specific PV system typologies for each type of land use (or water). Economic considerations were left out of scope. As our assessment focusses on the year 2050, we do not consider the growth rate of PV systems to be a limiting factor. However, we do take into account that a gradual growth pathway from now to 2050 means that the cumulative installed capacity in that year is a population of systems that were installed during the decades before.

2.1. Overall setup of the assessment

Our approach consists of four key steps: (i) a spatial analysis in which we defined a set of relevant Land Utilisation and Water Types (LUWTs) relevant for PV, (ii) a definition of one or more PV typologies for each LUWT, and (iii) an energy yield assessment for each typology. In the fourth step, policy relevant questions were translated into choices on LUWTs to be deployed for PV and typologies for each LUWT, and implications for the PV potential were calculated.

In the *spatial analysis*, a classification of Land Utilisation and Water Types (LUWTs) was set up. This classification of LUWTs was structured so that specific information on their total area TA (in km²) could be found in publicly available statistical datasets for the Netherlands, and that for each LUWT, one or more specific PV system typologies could be conceived, each with its specific energy yield.

As the next step, the various *PV typologies* (pt) for the different LUWTs were further elaborated. These typologies were defined on the basis of (i) the LUWT they can be applied on, (ii) their average horizontal orientation (azimuth θ , or horizontal deviation angle from the south; θ is defined as 0° for south orientation), (iii) their average slope (tilt α , or vertical angle), (iv) the technically maximum area coverage ratio (ACR_{max}), (v) the area fraction unavailable for PV panels due to edges and obstacles (F_{eo}), and (vi) the type of PV panels technically possible on the LUWT.

Finally, for the *energy yield assessment*, a specific annual energy yield per m² surface per typology (Y_a , kWh/m²/yr) was calculated according to Equation (1), as a function of:

- Specific yield (Y_s , kWh_{ac}/kW_p/yr), which depends on the yearly irradiation (with direct and diffuse components) and ambient temperature, the system location, the PV technology class, α , θ , and a performance ratio PR that, for the sake of simplicity accounts for a

wide variety of yield reductions and losses, including inverter, cable and soiling losses, mismatch effects and small-scale object and obstacle shading effects;

- Specific power (P_s , kW_p/m² of PV system), calculated as solar irradiation power under standard test conditions (STC, 1000 kW/m²) times panel efficiency (η , in %);
- Panel density, projected on the horizontal plane (D_p , in %).

$$Y_a = Y_s \times P_s \times D_p \quad (1)$$

2.2. Spatial analysis

For the determination of the potential area for PV on *buildings*, we used the *Basisregistratie Adressen en Gebouwen* (Base Registration Addresses and Buildings, BAG) (Anonymous, 2020a), as provided by the Dutch Land Registry, as a basis. The classification of building types as available in this source was partly clustered and partly further refined, in order to sufficiently differentiate between applicable PV typologies. For the 3D character of buildings, essential for estimating the ratio between building volume and its rooftop area, and for estimating façade potentials, three sources were used: Arcadis Shape Factors (Brand et al., 2017), Esri Map (Anonymous, 2020b) and 3D BAG (Anonymous, 2020c). For rooftop orientation and the ratio between flat and pitched roofs, no statistical data were available. As most rooftop orientations in the Netherlands have not been optimised for PV production, we assumed an even distribution of building façades and rooftops over all four cardinal wind directions. From our daily experience, we estimated that 80 % of ground-bound dwellings and other buildings have pitched rooftops while 20 % of them have flat ones. On the same basis, apartment buildings and other stacked buildings were assumed to have 100 % flat rooftops. This led to a classification into nine rooftop and three façade categories.

For the determination of the potential area for PV on *infrastructure* (including courtyards) and *green areas*, the *Basisregistratie Grootchalige Topografie* (Base Registration Large-Scale Topography) (Kadaster, 2020) from the Land Registry was the prime source, as this dataset contains all areas that are not buildings nor water. Also in this set, the existing classification was partly refined in order to create categories relevant for PV typologies. For example, the category ‘courtyards’ was split into three categories, viz. courtyards of dwellings, of commercial buildings, and farmyards, using data from the *Bestand Bodemgebruik* (Dataset Land Use) (CBS, 2018) from CBS (Statistics Netherlands). This led to thirteen categories for infrastructure and courtyards and nine for green areas.

For the determination of the potential area for PV on *water*, a distinction was made between inland and offshore waters. The base classification of the *Basisregistratie Grootchalige Topografie* was used. For inland waters, this was further refined using the *Watertypenkaart* (Map of Water Types) (Van Puijenbroek and Clement, n.d.) by PBL, the Environmental Assessment Bureau. For example, waters that are part of the Natura2000 European network of nature areas were specifically identified. Also a differentiation on wave heights was included. This led to six inland water categories and three for marine waters.

For all these LUWTs, full details of the translation of the various (sub) categories in the datasets into our classification can be found in a detailed background report (in Dutch) (Hooff et al., 2021). This report also contains stylised visuals of each typology, and photographs of real cases.

A possible point for critique may be that the applied databases indicate today's land use, not that of 2050. This in contrast to the energy analysis, in which we do consider an expected further performance improvement of PV systems over that period. This approach was chosen because technical performance improvement over the coming decades will significantly influence the 2050 potential, while in our view land use change will have a more limited impact. Besides, technical outlooks for future PV performance are widely available, while we only found one literature source for future land use change (Manders and Kool, 2015),

which does not provide the level of detail needed for the set of land use types in this study. Nevertheless, in the Discussion (section 5.2), we indicatively show the effect of land use change on the various potentials.

2.3. Energy yield assessment

For the estimation of *specific yields* (Y_s), we used the PVGIS tool (Anonymous, 2020d). This tool could not be applied for three typologies, in which case we used an alternative source for a Y_s estimate: bifacial systems (Janssen et al., 2015; Romijn, 2017), vehicles and ships (Centeno Brito et al., 2021; Ham, 2019), and offshore PV (Golroodbari and van Sark, 2020).

For the calculation of *specific power* (SP), we needed an estimate of the average efficiency of the systems operating by the year 2050, which will be an average of all systems installed in the years until then. We calculated this from data estimates for newly sold systems in 2020, 2030 and 2050, with the assumptions that (i) there would be a linear efficiency development in the years in-between, (ii) installed PV capacity develops linearly between now and 2050, and (iii) there is an annual degradation rate. We used this efficiency for all typologies, although for some innovative ones, lower efficiencies may be assumed as specific conditions apply to them (such as coloured building integrated PV, or a thick protective layer on systems on road pavements). Currently available literature on such effects appeared insufficient to quantify these effects into a different efficiency assumption.

The calculation of the *typology-specific panel density* (D_p) depends on panel slope α and on the nature of the surface. On the basis of standard goniometry, we used different formulas to calculate panel densities related to the horizontal plane potentials of pitched and flat panels ($\alpha \neq 90^\circ$, Equation (2)) and of vertical panels on horizontal surfaces ($\alpha = 90^\circ$; Equation (3)), and panel densities related to the vertical plane potentials of façades ($\alpha = 90^\circ$, Equation (4)). In Equation (2) and (4), ACR_{max} is the technically maximum area coverage ratio, F_{eo} is the area fraction unavailable for PV panels due to edges and obstacles, and df the distance factor.

ACR_{max} and F_{eo} are determined on the horizontal surface, actual for flat surfaces and projected for pitched ones. In Equation (3), df is the distance factor (the ratio between the distance between array of panels and the height of the PV panel part of the array).

$$D_p = \left(\frac{(1 - F_{eo}) \times ACR_{max}}{\cos \alpha} \right) \quad \text{if } \alpha \neq 90^\circ, \text{ on pitched and flat surfaces} \quad (2)$$

$$D_p = \frac{1}{df} \quad \text{if } \alpha = 90^\circ, \text{ on flat surfaces} \quad (3)$$

$$D_p = (1 - F_{eo}) \times ACR_{max} \quad \text{if } \alpha = 90^\circ, \text{ on façades} \quad (4)$$

2.4. Assessment of PV potential and impacts of policy options and choices

PV potentials were assessed as follows. For each LUWT, we defined the relative shares (RS) of each PV typology (pt), and the PV potential on that LUWT was calculated by summing up the relative share of each typology times its corresponding specific annual energy yield Y_a . Next, we defined the share of area used (SAU) for each LUWTs, and total PV potential Y was calculated by summing up total area (TA) per LUWTs times its share of area used (SAU) times its PV potential. See Equation (5). For some policy choices, this analysis was reduced to a limited set of LUWTs and/or typologies. In order to accommodate for areas that are inherently unfit for PV, e.g. due to large-scale shading effects from neighbouring buildings, SAU was maximised at 80 %.

$$Y = \sum_{LUWT=1}^m TA^m \times SAU^m \times \left(\sum_{pt=1}^n RS^n \times Y_a^n \right) \quad (5)$$

We do not aim to provide one overall or maximum potential for PV in the Netherlands as it is simply not realistic to assume that all the

available land and water surface of the country would be covered by PV panels. Our focus is rather to have an analytical framework available to assist policy makers by providing them with relevant quantitative information for current and future policy-relevant questions. For this, we first explored possibly interesting policy questions and options by brainstorming among the author team, followed by informal interaction with several policy makers, and iteration on preliminary ideas within the team. Next, we translated these ideas into parameters, as different shares of LUWTs to be deployed for PV (the SAUs in Equation (5)), and the (mix of) typologies to be assumed on them (the RSs in Equation (5)). For some questions, we developed more than one variant for the translation of policy perspectives into LUWT shares and typologies, in order to show the implications of different choices. Finally, we discussed preliminary outcomes with policy makers to further improve their illustrative character, and in some cases, this led to, changes in the variants.

For the translation of policy options into parameters, we took the following approach. The shares of area used for the various LUWTs and the mixes of typologies should directly relate to the policy question and reflect possible freedom of choices therein. Furthermore, the mix of typologies contains currently available and more innovative, upcoming ones. Some of these upcoming typologies will likely become available in the next 5–10 years at no or marginal extra costs (e.g. solar carports, lightweight rooftop panels, bifacial tracking systems). Others are 'high risk - high potential' options, that may become available in more than 10 years at the earliest and still face major technological and cost challenges but, when available, could provide a significant contribution (e.g. offshore PV systems and systems integrated in roads). These considerations should be taken into account when applying the typologies. Furthermore, the choice of typologies is not entirely without restrictions. For example, the mix of typologies on pitched rooftops (South, East-West and North) is determined by the spatial orientation of the current and future building stock. Consequently, there will always be a certain share of rooftops with a (less attractive) North orientation. Obviously, this share will decrease if rooftop suitability for PV systems becomes a design criterion for newly built homes.

3. Input data

3.1. Spatial analysis

With the data sources and refinements as mentioned in Section 2.2, the available area for each LUWT is given in Table 1. The dataset shows that of the circa 40.000 km² of inland area in the Netherlands, about three quarter (or almost 30.000 km²) consists of green areas (LUWTs #26–34 in Table 1), of which almost 20.000 km² is agricultural (LUWTs #26–28) and more than 10.000 km² is grassland (LUWT #28). Built areas (LUWTs #1–8) and paved areas (LUWTs #13–25) jointly consist of over 5.000 km², which is roughly equal to the area of inland waters. The allocation of LUWTs over the country can be indicatively seen in Fig. 1; note that in this map, infrastructure is not explicitly depicted, and the typology is not entirely consistent with that in Table 1.

3.2. PV system typologies

Table 2 shows the various typologies we defined, the LUWTs they can be applied on, and their corresponding input data. Examples of the stylised visuals constructed for each of them can be found in Fig. 2; a full set is in the background report (Hooff et al., 2021). The typologies were constructed with the following considerations:

- On *dwellings*, PV systems can be *building applied* (BAPV) and *building integrated* (BIPV). We made separate typologies for key rooftop geometries, distinguishing flat and pitched rooftops, and South, East-West en North orientations. The façade typologies also differ for these orientations.

Table 1

Available areas per land utilisation type numbered 1 to 43.

Land use Type	Total area (km ²)	Land use Type	Total area (km ²)	Land use Type	Total area (km ²)
Buildings: rooftops dwellings (total)	550	Infrastructure (total)	4.200	Inland waters (total)	5.200
1. Land-based dwellings	460	13. Roads	1.000	35. Water basins	10
2. Apartment dwellings	90	14. Bicycle paths	100	36. Other inland waters	14
Buildings: rooftops other build. (total)	610	15. Walkways	300	37. Rivers, channels, ditches	1.200
3. Commercial service buildings	100	16. Airport runways	10	38. Other waters, wave cat. 1–2 ³	900
4. Public service buildings	30	17. Railroads ²	50	39. Other waters, wave cat. 1–2 ³ , Natura2000	550
5. Industrial buildings	170	18. Parking areas	110	40. Other waters, wave cat. 3 ³ , Natura2000	2.500
6. Large outbuildings (>20 m2)	250	19. Waste landfills	5		
7. Small outbuildings (<20 m2)	25	20. Roadsides	600		
8. Other rooftops	30	21. Noise barriers	5	Marine waters (total)	62.000
		22. Vehicles and ships	70	41. Wave cat. 3	2.500
9. Greenhouses ¹	140	23. Courtyards of dwellings	1.000	42. North Sea, within municipal boundaries	1.000
		24. Other courtyards	800		
		25. Other paved lands	180	43. Other North Sea	61.000
Buildings: façades (total)	2.200	Green areas (total)	28.000		
10. Land-based dwellings	1.100	26. Arable lands	7.900		
11. Apartment dwellings	300	27. Orchards	380		
12. Service and industry	800	28. Grasslands	10.900		
		29. Woodlands	3.400		
		30. Open nature	1.100		
		31. Other nature areas	1.100		
		32. Farmyards	1.200		
		33. Courtyards nature areas	90		
		34. Recreational areas, parks	1.400		

¹: On greenhouses, we assumed that PV systems would not be realized due to light competition with the crops. Therefore, this LUWT has no typology in Table 2.

²: On railroads we also assumed that solar-PV systems would not be realized, for practical and technical reasons.
³: Wave category 1–2: wave height up to 0,6 m, category 3: between 0,6 and 1,2 m. North Sea is wave cat. 4 (>2 m)

- On *service sector* buildings, flat rooftops dominate the population of buildings in the Netherlands. Only for agricultural barns, simple field observation shows that pitched rooftops are the standard.
- On *infrastructure*, many LUWTs have their own specific typology with corresponding input data (see Table 2).
- On *green areas*, PV systems may vary in their horizontal orientation, slope, and panel density. Besides, innovative concepts exist that use bifacial panels, either in a vertical orientation or in a system tracking the sun position.
- On *water*, essentially the same systems as on green areas can be conceived, although sun-following systems are less probable and were therefore excluded. Besides, a pontoon system was also investigated.

For all typologies, the data inputs θ , α , ACR_{max} , F_{eo} and SF were estimated using available information from four sources: (i) written and oral information from designers and developers of PV parks, (ii) Information from Google Earth on parks and rooftop systems, (iii) scientific papers on several innovative products and concepts (Centeno Brito et al., 2021; Golroodbari and van Sark, 2020; Ham, 2019; Janssen et al., 2015; Romijn, 2017), and (iv) product sheets and photos of demo sites with some of the innovative products.

3.3. Energy analysis

For the calculation of *specific yield* in PVGIS, factors α and θ were differentiated between the typologies (see Table 2). Crystalline silicon (c-Si) was taken as the PV technology class as this dominates the market today. As reference geographical location the city of Utrecht was taken, located in the centre of the Netherlands. For the irradiation we took the ERA5 database available in the PVGIS tool. For the yield reductions and

losses at both module and system level, we assumed 0,15 for buildings and infrastructure, and 0,10 on other typologies. This differentiation was based on the higher levels of shading and soiling due to air pollution that urban systems are exposed to. Finally, for the PVGIS parameter on surface characteristics, systems on buildings and infra were considered to be ‘building integrated’, and other typologies ‘detached’. This parameter mainly corrects for differences in temperature impacts. Combined, the latter two assumptions lead to a performance ratio PR of 0,80 for buildings and infrastructure and 0,85 for other typologies. These numbers typically lie between conventional values (Moratis and Sark, 2014) on the one hand and values for more advanced systems (Sinapis et al., 2021) and future expectations (Reich et al., 2012) on the other.

For the calculation of *Specific Power*, the IEC standard was taken (International Electrotechnical Commission, n.d.). Recent panel efficiencies were estimated at 17,3% by an HIS Markit analysis (Anonymous, 2019a). Estimations of future average STC- efficiencies of newly sold PV panels vary between 22 and 25 % by 2030, and between 24 % and more than 30 % by 2050 (Anonymous, 2019b; Mayer et al., 2015; Sinke et al., 2016). On this basis, we assumed an 18 % efficiency for 2020, 23 % for 2030 and 30 % for 2050. Furthermore, from our market knowledge, we assumed an average lifetime for PV systems of 27 years (nominally 30 years, with a correction for some systems being decommissioned earlier), and a degradation rate of 2 % in the first year and 0,5%/y in the years afterwards (Mayer et al., 2015). With the interpolation methodology described in Section 2.3, this leads to an average STC-efficiency of PV systems operating in 2050 of 23 %. For each typology, these assumptions lead to energy yield estimates as given in the far-right column of Table 2. Annex A of the background report (Hooft et al., 2021) contains a full accounting of each individual data assumption per typology.



Fig. 1. Land use in the Netherlands 2015 (main map (Environmental Data Compendium, 2020)) and Dutch marine waters (lower right insert) (Hooff et al., 2021)).

3.4. Assessment of policy options

Along the lines described in Section 2.4, we developed specific mixes of LUWTs and applied typologies therein for every policy question and related variant(s). It goes beyond the scope of this paper to present this full set of detailed data inputs; this can be found in the background report (Hooff et al., 2021). As an illustration, we include an example translation of a generic area share into LUWTs and typologies in Table 3, in which we considered relevant current views of national and local authorities and interest groups, such as exclusion of nature areas for PV, limiting the use of agricultural land for PV (while encouraging PV on all kinds of farm rooftops). In our analytical framework, we can easily vary the relative contributions of each LUWT and in the shares between the possible typologies on each LUWT. This was done for various policy-relevant questions.

4. Results: Impact assessment of several policy questions and choices

4.1. How do these potentials relate to the ambitions for PV in the Netherlands?

Several recent energy transition scenarios for the Netherlands provide projections for the role of PV in a decarbonised energy system (Den Ouden et al., 2020; Scheepers et al., 2020). These studies are relatively consistent in the estimate of circa 80 GW_p as a relatively high, though not maximum estimate of PV to be installed by 2050, or 70 TWh/yr of electricity generation. This can be realised by various mixes of LUWTs. In Table 4, two illustrative examples are specified, that only use LUWTs on which PV is being developed today already: a variant focussing on rooftops, in which capacities on other LUWTs are limited to levels that have been committed and/or realised today, and a variant in which a balanced mix is sought over the LUWTs (except on sea), that can probably be realised faster than a variant with focus on rooftops only. Of

course, many other combinations are possible. Full details on the build-up of the LUWTs from the various typologies, for these cases and the ones in section 4.2 can be found in the background report (Hooff et al., 2021).

The examples indicate that such a 70 TWh/yr projection can be met with relatively limited spatial impact: rooftops alone already provide ample potential for this, and less than a third of the available rooftop area would suffice. Besides, opening up other LUWTs (on land and inland water) significantly reduces the required areas on rooftops.

For comparison, Table 4 also contains indications of current (2020) spatial use and electricity production of PV systems, based on recent information on capacities (DNE research, 2021) and related LUWTs (CBS, 2020; RVO, 2021), as well as projections for 2030, production based on the latest reference outlook (PBL et al., 2020), and related LUWTs (CBS, 2020; PBL et al., 2020; RVO, 2021; Wiebes, 2021). Average PV efficiencies for 2020 and 2030 were calculated with the same approach as for 2050, indicated in Section 2.3.

4.2. To what extent is there room for higher ambitions?

In future energy scenarios, the role of PV can be limited by several factors, including area availability, potentials and techno-economic developments of PV and other energy technologies (including energy storage and conversion), and system integration issues of PV as an intermittent source of electricity. Scenario studies are usually not very transparent on the exact considerations that determine the contributions of the different supply options. Therefore, it may be well possible that the role of PV may be limited by relatively conservative assumptions on spatial availability. In order to accommodate for this, we developed some variants for PV that would meet a significantly higher ambition level for 2050 than the currently known scenarios: 200 TWh/yr instead of 70.

These variants, also shown in Table 4, suggest that even this ambition level is still possible by only modestly increasing the pressure on

Table 2

Key data inputs for the PV typologies (full substantiation in (Hooff et al., 2021)), and their resulting energy yield (EY).

PV typology	Applicable to LUWTs (Table 1)	Av. horiz. orient. (θ) ¹	Average slope (α)	Max. area coverage ratio (ACR _{max})	Fraction unavailable F _{eo}	Energy yield (Y _a) GWh/km ² /y
Dwellings						
a. Pitched roof South (BAPV)	1	22,5°	40°	0,99	0,35	182
b. Pitched roof E-W (BAPV)	1	90°	40°	0,99	0,35	145
c. Pitched roof North (BAPV)	1	157,5°	40°	0,99	0,35	97
d. Pitched roof South (BIPV)	1	22,5°	40°	0,99	0,20	224
e. Pitched roof E-W (BIPV)	1	90°	40°	0,99	0,20	178
f. Pitched roof North (BIPV)	1	157,5°	40°	0,99	0,20	119
g. Flat rooftop South (BAPV)	2	22,5°	11,5°	0,75	0,35	100
h. Flat rooftop E-W (BAPV)	2	90°	11,5°	0,92	0,35	112
i. Façade South	10,11	22,5°	90°	0,99	0,75	39
j. Façade E-W	10,11	90°	90°	0,99	0,75	28
Service sector buildings						
k. Flat rooftop South	3–8	22,5°	11,5°	0,75	0,30	108
l. Flat rooftop E-W	3–8	90°	11,5°	0,92	0,30	121
m. Flat rooftop flex ²	3–8	n.a.	3°	0,95	0,20	116
n. Agricultural barn South	6–7	22,5°	30°	0,99	0,10	235
o. Agricultural barn E-W	6–7	90°	30°	0,99	0,10	194
p. Agricultural barn North	6–7	157,5°	30°	0,99	0,10	144
q. Façade South	3–7	22,5°	90°	0,99	0,50	77
r. Façade E-W	3–7	90°	90°	0,99	0,50	55
s. Other (curved, shaped)	3–5	45°	20°	0,80	0,50	86
Infrastructure						
t. In road	13–16	n.a.	0°	0,90	0,10	150
u. On parking area	18, 23–25	45°	11°	0,75	0,05	147
v. On waste landfill, dike, wall	19	45°	20°	0,90	0,50	106
w. In noise barrier	21	90°	80°	0,90	0,05	224
x. On vehicles, ships	22	Variable	0°	0,99	0,70	38
Green areas						
y. South 11°	21, 26–34	22,5°	11,5°	0,75	0,15	142
z. South 30° high density	21, 26–34	22,5°	30°	0,50	0,15	115
aa. South 30° low density	21, 26–34	22,5°	30°	0,50	0,50	68
ab. E-W high dens.	21, 26–34	90°	11,5°	0,92	0,15	159
ac. E-W low dens.	21, 26–34	90°	11,5°	0,92	0,50	93
ad. E-W bifacial vertical l.d. ³	21, 26–34	90°	90°	0,99	0,15	44
ae. Sun-tracking bifacial	21, 26–34	Variable	Var., av. 45°	0,35	0,15	86
Water						
af. South 11°	35–43	22,5°	11,5°	0,75	0,15	151
ag. South 30° high density	35–43	22,5°	30°	0,50	0,15	122
ah. South 30° low density	35–43	22,5°	30°	0,50	0,50	73
ai. E-W high density	35–43	90°	11,5°	0,92	0,15	169
aj. E-W low density	35–43	90°	11,5°	0,92	0,50	92
ak. E-W bifacial vertical l.d. ³	35–43	90°	90°	0,99	0,15	46
al. Flat on pontoon	35–43	Variable	10°	0,50	0,02	100

¹ : Average absolute deviation from perfect South orientation (0°).² : Typology makes use of thin-film PV modules that are flexible and can be glued on rooftops.³ : Additionally, the distance factor (df) was assumed to be 4 and the height fraction of the support construction (x) 0,5.

green areas: if rooftops are used almost to the maximum of their potential and infrastructure contributes a substantial share, the amount on (agricultural or other) land can remain limited to the areas that have already been realised as solar parks today and the ones that have been permitted by 2020. In the balanced variant, in which all land and water areas contribute ~ 1 to 5 % of their potential, the use of rooftops can remain limited to 40 % of theirs.

4.3. What new area/typology combinations could offer significant additional potential?

While the 70 TWh variants only make use of LUWTs on which PV systems are already being realised today, the 200 TWh variants illustrate that some new combinations of LUWTs/areas and typologies can open significant new potential, see Table 5.

This is most striking for offshore PV. The circa 200 TWh/yr offshore PV potential corresponds to using 50 % of the available area within offshore wind parks, if these are deployed to 60 GW, the upper ranges in the energy scenarios for 2050 (Den Ouden et al., 2020; Scheepers et al., 2020). This also means that the 20 TWh/yr in the balanced elaboration

of the 200 TWh ambition (Table 4) can be well accommodated within the 11,5 GW offshore wind parks that are already foreseen for 2030 (Anonymous, 2019c).

Carports (in our analysis part of the infrastructure LUWT category) have also been proposed as a relevant additional option for providing space for PV systems. This is confirmed in our analysis: PV systems covering public and company car parks would provide an additional potential up to circa 25 TWh/yr, or more than a third of the maximum deployment on dwelling rooftops in Table 4. Obviously, carport PV is more expensive in terms of mounting system costs.

Currently, experiments are also being done with PV integrated in roads (Anonymous, 2021a, 2021b). As is shown in Table 5, particularly roads could offer a significant additional potential for PV power production of up to 50 TWh/yr in total. However, further innovations will be needed to attain the required function integration, as well as demos to gain practical experience, before this option can reach the stage of volume growth (Hooff and Sinke, 2019).

PV on façades of buildings also seem to offer significant additional potential: according to our analysis, façades could add more than 30 TWh of potential to the almost 150 TWh on rooftops (see Table 5).

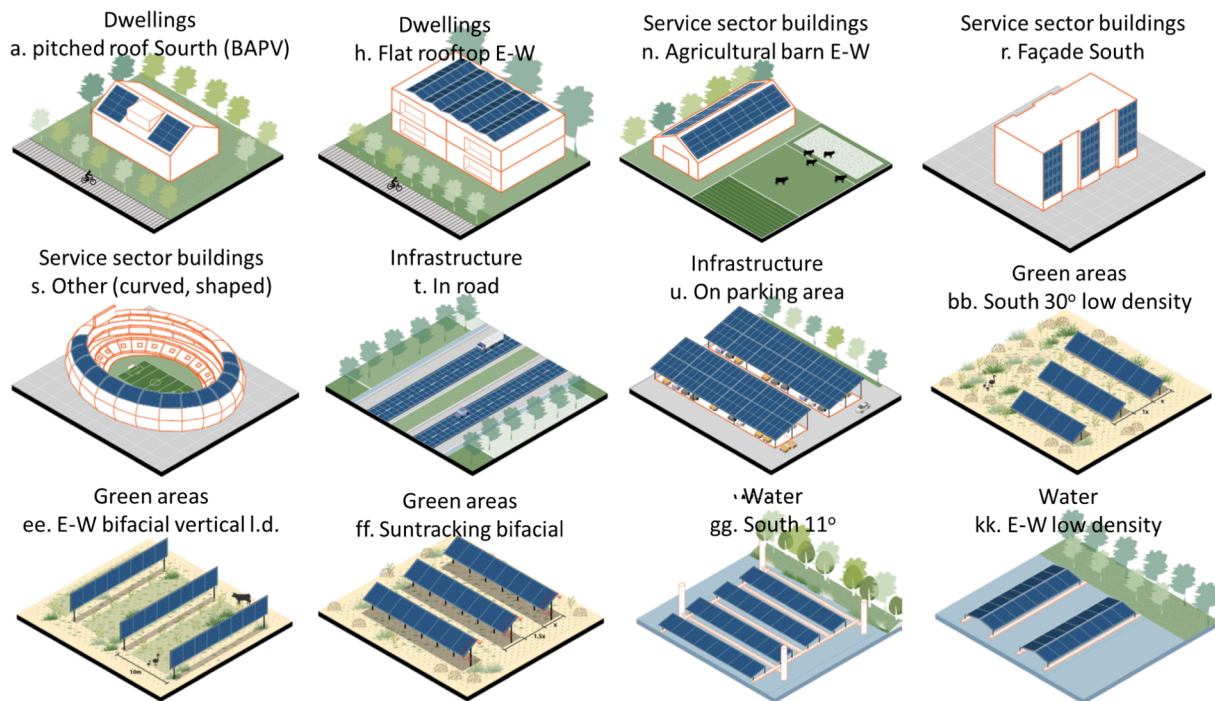


Fig. 2. Examples of the visual elaborations of the various typologies; letter codes refer to Table 2 (Hooff et al., 2021).

Building-integrated PV (BIPV), as an alternative to simply adding PV panels to rooftops (BAPV) does not provide significant additional potential in terms of PV power production but adds ca 15 % to that of rooftops of dwellings, mainly because BIPV will probably enable solar systems to better use the available area on rooftops. Aesthetical reasons will be an additional reason for the further development of BIPV; the impact of this characteristic on its spatial potential has not been explored further.

4.4. What if residential rooftops are used for maximum production instead of covering household demand?

Current net metering policy and tariff structures in the Netherlands provide an incentive for households to install PV-systems that generate an annual production no larger than the annual household consumption (Londo et al., 2020): the value of a kWh PV-produced power that replaces own consumption (directly or indirectly) is significantly higher than that of a kWh that is net delivered to the grid. Because of this, it is likely that a substantial part of the potential on rooftops will remain unused. Table 5 also shows the full potential of PV on residential rooftops and compares it with projected electricity demand of households as assessed in a recent energy scenario study for the Netherlands (Den Ouden et al., 2020). Although this comparison simplifies reality (demand and potential would need to be compared for each individual dwelling, not on national level), these data do suggest that current policy and tariff structures leave a significant part (more than 50 % in this calculation) of the potential on residential rooftops untapped. This number applies when we calculate with future system efficiencies and electricity demand, but also when we do so with current numbers for both (not shown in Table 5). This is a relevant insight particularly if policy makers intend to focus on PV on rooftops and want to keep pressure on land and water areas low.

4.5. What is the impact of choosing either spatially intensive (limited multifunctionality) PV systems or less intensive (more multifunctionality) PV systems on green areas?

In the current policy debate on PV, deployment on land is a much-

discussed topic (Carlisle et al., 2015; Kaldellis et al., 2013). In this context, there is a significant difference between development of intensive, almost monofunctional solar fields, and less intensive, multifunctional designs in which there are more possibilities for other functions such as agriculture, recreation, biodiversity, and integration into the surrounding landscape (Schotman et al., 2021; Uytterlinde et al., 2017).

In Table 6 we show the potential for PV on 1,6% of all green areas (consistent with the ‘balanced mix’ 200 TWh/yr variant in Table 4), in our (relatively intensive) reference mix of PV typologies, and a less intensive, more multifunctional variant. This alternative variant roughly halves the potential for PV per km², from 2,1 to 1,1 GWh/ha/yr, meaning that for the same potential, twice the amount of land would be needed. Alternatively, this could be compensated for by e.g. deploying PV on more rooftops (all types), i.e. with 20 percent points of total rooftop area.

4.6. What could be the impact of a focus on highest yields per m² instead of least cost per m²?

Obviously, the efficiency of PV systems has an impact on spatial potentials. Here, we explore two aspects that may have an impact on our assumption on system efficiencies:

- Global RD&D efforts still lead to an ongoing improvement in PV efficiencies and yields per m². Even for highly qualified experts it is still difficult to project efficiencies in 2050. We estimate that an uncertainty range between –2 and + 5 percent points on our 23 % assumption for the average existing PV system by 2050 is reasonable.
- Particularly in a densely populated country like the Netherlands, PV investors may focus on highest energy yields per m² instead of least costs per kWh, viz. choosing the most spatially efficient systems available on the market. Currently, most commercially available PV panels have efficiencies between 18 and 20 %. Here, we assume that this 2 percent point range remains stable over time.

The impact of this range in yield per m² on spatial impact is substantial. For example, an average 2 percent point higher efficiency

Table 3
Example of an elaboration of a variant into typologies, for the contribution on Green areas in the case of a 70 TWh/yr ambition, variant ‘balanced development’. For the complete list of typologies per LUWT see (Hoof et al., 2021).

LUWT	Total area (km ²)	Share of area used	Typology							km ²	TWh/yr
			z. South 11°	aa. South 30° high density	ab. South 30° low density	ac. E-W high density	ad. E-W low density	ae. E-W bifacial vertical	af. Sun-tracking bifacial		
Green areas	28.000	0,7%								192	16.7
26. Arable lands	7.900	0,8%	10 %	20 %	20 %	10 %	10 %		20 %	63	5.4
27. Orchards	380	0 %									
28. Grasslands	10.900	0,8%	10 %	20 %	20 %	10 %	10 %		20 %	87	7.4
29. Woodlands	3.400	0 %									
30. Open nature	1.100	0 %									
31. Other nature areas	1.100	0 %									
32. Farnyards	1.200	5 %		25 %		25 %		50 %		42	3.9
33. Courtyards nature areas	90	0 %									
34. Recreational areas, parks	1.400	0 %									
		km ²	15	30	41	26	15	36	30		
		TWh/yr	1.3	2.6	3.5	2.3	1.3	3.2	2.6		

Table 4
Examples of possible shares of PV on different LUWTs summing up to 80 GW_p capacity, as mentioned in several decarbonization scenarios, and to 250 GW_p capacity, as an illustration of a very high ambition level.

LUWT	Total area (km ²)	2020 Situation			2030 Projection			2050 Ambition level: 70 TWh/yr					
								Variant ‘priority on rooftops’			Variant ‘balanced development’		
		Share of area used	Electricity production (TWh/yr)		Share of area used	Electricity production (TWh/yr)		Share of area used	Electricity production (TWh/yr)		Share of area used	Electricity production (TWh/yr)	
Rooftops dwellings	550	6,4%	3,5	13 %	8,5	24	15 %	12	65	80 %	40 %	32	
Rooftops other buildings	610	4,6%	2,8	13 %	9,5	28	15 %	14	78	80 %	40 %	39	
Infrastructure	4.200	0 %	0	0,2%	1,3	10	1,6%	16	49	5,3	4,7%	41	
Green areas	28.000	0,07 %	1,8	0,14 %	3,7	4	0,7%	16	4	0,1%	1,6%	42	
Inland water	5.100	0,04 %	0,1	0,14 %	0,6	4	2,3%	12	4	0,7%	4,8%	24	
Offshore	62.000	0 %	0	0 %	0	0	0 %	0	0	0 %	0,4%	22	
Total		8,3	27,5		70	70		200	200			200	

Table 5

PV potential on several specific LUWTs, and for specific typologies on some of them.

	Total area (km ²)	Share of area used	Energy yield (TWh/yr)	PV capacity (GW _p)
Offshore PV (42)	61,000	3,5%	200	230
Public parking space (18)	110	50 %	8	9
Parking space at other courtyards (24)	800	15 %	18	21
Total parking areas			26	30
Roads (13)	1000	33 %	40	50
Bicycle paths (14)	100	33 %	5	6
Walkways (15)	300	33 %	4	5
Total road			50	60
Façades (residential dwellings)	1100	20 %	7	12
Façades (apartment dwellings)	300	40 %	5	10
Façades (service and industry)	800	40 %	20	36
Total façades			32	58
Total rooftops (BAPV)	1100	80 %	57	75
Total rooftops (BIPV)	1100	80 %	66	89
Rooftops land-based dwellings	460	80 %	52	69
Rooftops apartment dwellings	90	80 %	7	9
Façades land-based dwellings	1100	20 %	7	12
Façades apartment buildings	300	40 %	6	10
Total potential households (roofs, façades)			72	100
Electricity consumption households 2050			35–40	
Ratio consumption/rooftop potential			50–60 %	

reduces the required area by approximately 40 km² in the 70 TWh/yr balanced variant. If this area reduction is allocated only to green areas and inland waters, this reduces their required area by 13 %. Obviously, the 5 % uncertainty range has a factor 2,5 stronger impact.

5. Discussion

5.1. On the results

While we merely answered several ‘what if’ questions, we also compared our results with other studies that estimated PV potentials on various land use types in the Netherlands. This comparison is summarised in Table 7.

On *rooftops* and *façades*, our study provides a significantly higher maximum potential than all other studies considered. These differences however can mostly be explained by differences in assumptions on (i) the maximum use of available rooftop area, and (ii) average energy yield by 2050. For example, the study with a relatively low estimate for rooftop potential, [Sijmons et al \(2017\)](#) assume 27 % rooftop coverage while our maximum estimate of 80 % of available area is considerably higher. Given the time frame of 2050 we are confident that a significant share of rooftops that may not be suitable for PV systems today (e.g. because of construction weaknesses) will be so by 2050. Besides, [Sijmons et al.](#) assume the energy yield to be about a third of ours, which is based on a comprehensive analysis of current and foreseen efficiencies (see section 2.3). Only for [Defaix et al. \(2012\)](#) differences in assumed areas of rooftops and façades contribute to the difference in potential estimate between their study and ours.

For PV on *infrastructure*, assessments vary widely and cannot be compared very well on their underlying assumptions. Here, our study falls relatively central in the band width of estimates.

For PV in *green areas*, differences with two other studies can be

entirely explained by a different assumption on the maximum acceptable area coverage, which is of course value laden. The other study is not explicit on this assumption, with makes comparison more difficult.

Finally, for PV on *inland waters* and *offshore* areas, potential studies are scarce, and differences among them are significant. Here, the key determining factor is the availability of area. For example, [Druten and Kruit \(2019\)](#) base their inland waters potential on an area from which considerable tracts of water are excluded beforehand. For their offshore potential, differences can be mainly explained by a lower assumption on future offshore wind parks (in which offshore PV can be developed), and a lower share of area within these parks available for PV.

5.2. On the methodology and data

On our *spatial analysis*, our impression is that our method is relatively consistent. Besides the datasets we used for the area assessment are known for their quality and reliability, quite understandable for a densely populated country such as the Netherlands in which all available space is used intensively. The spatial potentials as estimated in this study are based on the datasets consulted in 2020. Obviously, there will be land use changes in the course towards 2050. Particularly, further urbanisation and conversion of agricultural land to nature areas can be expected. The most explicit projection of such developments between 2020 and 2050 in the Netherlands can be found in the WLO scenarios ([Manders and Kool, 2015](#)). In these scenarios, the area of agricultural land decreases by 5–8 % during these decades; roughly half of this is redeveloped as nature area and the other half for urbanisation. Given current areas for agriculture (ca 20.000 km²), nature and urban area (both ca 5.000 km²) this means that the latter will increase by 10–15 %. The scenarios do not further distinguish the developments in underlying LUWTs, for urbanisation, e.g. between dwellings, infrastructure, and parks in cities. Therefore, it was not possible for us to include these

Table 6

Comparison of PV capacities to be realized on 1,6% of green areas, in an intensive, monofunctional variant versus a less intensive, multifunctional variant.

Variants	Typologies (all field systems)						Total potential	
	y. South, 11°	z. South, 30° high density	aa. South, 30° low density	bb. East-West, 10–13° high density	dd. East-West, vertical, bifacial	ee. Sun-tracking, single axis, bifacial	Energy yield (TWh/yr)	Installed capacity (GW _p)
Current mix	30 %	30 %	10 %	30 %	–	–	58	63
Less intensive	–	10 %	30 %	–	30 %	30 %	31	34

Table 7

Comparison of the possible electricity on various LUWTs from various studies.

Ref	Rooftops			Façades			Infra		Green areas		Inland water		Offshore	
	Supply (TWh/yr)	Area cov.	EY (kWh/m ²)	Supply (TWh/yr)	Area cov.	EY (kWh/m ²)	Supply (TWh/yr)	Area cov.	Supply (TWh/yr)	Area cov.	Supply (TWh/yr)	Area cov.	Supply (TWh/yr)	Area cov.
This study	143	80 %	100–180	32	20–40 %	28–77	49	5,3%	42	1,6%	24	4,8%	22	0,4%
(Defaix et al., 2012)	23	40 % ¹	162	8	20 % ²	114								
(Folkert and Wijngaart, 2012)	34													
(Lemmens et al., 2014)	50		120											
(Veenstra, 2015)	57		120				50–172							
(de Jager et al., 2017)	58–65		120				172		44	2 %				
(Sijmons et al., 2017)	25	27 %	50				10		20					
(Folkerts et al., 2017)	87	30 %	130–210				28		38	1,5%	23	4 %	43	
(Anonymous, 2018)	60	48 %	140											
(Quintel Intelligence, 2020)	32													
(Druten and Kruit, 2019)											3	3–5 % ²	2,5	n.a. ³

Table footnotes.:

¹: Of a total rooftop area estimate of ~ 250 km², considerably lower than the other studies reviewed.²: Only South-facing façades considered.³: Percentage of inland water area with exclusion of several water types, among which inland navigation waterways, Natura2000 areas, waters with a recreational function and waters smaller than 0,5 km².⁴: Correlated with the development of offshore wind: 1 MW offshore PV for each 10 MW of offshore wind capacity, with an assumption of 25 GW offshore wind capacity addition in the period 2025–2050.

scenarios in our analysis on the level of LUWTs and specific typologies. As these relative land use changes roughly fall within the uncertainty range of circa 10 % that we would indicate for our overall analysis, we consider it defensible that we have not taken these developments into account any further.

In our *energy analysis*, again we believe that our methodology is relatively straightforward. In the data assumptions, the future performance of PV systems towards 2050 is a major uncertainty, in which we see that its development over the two decades has accelerated (Mayer et al., 2015) and has generally exceeded earlier expectations (MacKay, 2009). Besides, the assumption of a constant absolute growth of PV systems (not an exponential growth) leads to a relatively conservative estimate of overall efficiencies by 2050.

The translation of what-if questions to distributions over PV typologies is a step that cannot be entirely objectivated and is at least partly value-laden.

5.3. Limitations

This study only focusses on the *spatial* potentials for PV. While this is an important aspect of its future role in a sustainable energy economy, several others are also relevant. In the first place, technical and economic availability of innovative options, such as BIPV, solar roads and offshore PV will also affect the final allocation of PV power generation over the various LUWTs. Secondly, system integrations play a role, such as the degree by which PV systems can be integrated into the local and regional grids, and their supply can actually reach demand, and the degree to which flexibility options (on the demand and supply sides, and within the electricity infrastructure) will be able to accommodate for the variable nature of PV power generation (Jamil et al., 2017; Lupangu and Bansal, 2017). Thirdly, actual PV development will also greatly depend on social and institutional aspects, such as public acceptance of PV

(Carlisle et al., 2015, 2014; Kaldellis et al., 2013) particularly on land, water and infrastructure, on prosumer behaviour (Abreu et al., 2019; Engelken et al., 2018; Sommerfeld et al., 2017), particularly on rooftops of private dwellings, and on overcoming split incentive issues (Hong et al., 2017; Lang et al., 2016) particularly on rented dwellings and service buildings. Next to their impact on actual potentials, these considerations may also cause that PV potentials on some LUWTs can be realised at a higher rate than others. As CO₂ emissions should be reduced relatively fast in the coming decades, particularly in the power sector (IEA, 2021), this factor will also affect PV shares over the various LUWTs. In any integrated assessment on the perspectives for PV for the Netherlands, these factors should also be considered.

6. Conclusions

On the basis of the refined analysis provided in this paper, we conclude that the spatial potential for PV is substantial when compared to current projections of the long-term role of this option in a long-term decarbonised energy economy. In principle, these projections, and even a doubling of this volume, can be predominantly met by PV on rooftop areas; we have also sketched some variants with a more balanced allocation over the various land use types. This means that policy makers may focus on rooftop development for spatial quality reasons, although other considerations such as ease of grid connection and ease of project development may favour on-land development.

PV within offshore wind parks, on infrastructure, parking spaces and façades offer considerable opportunities for additional potential. These areas all still have their specific development issues and require further RD&D. For policy makers, it makes sense to include such applications in innovation programmes.

Current net metering programmes often provide an incentive for homeowners to dimension their solar home system on annual electricity

use. This incentive can leave a significant part of the rooftop potential of dwellings untapped. Therefore, if policy makers intend to reduce the pressure to develop PV fields on green areas, it is desirable to reshape this policy so that it stimulates homeowners to make full use of their available rooftop area.

Utility-scale land-based PV systems can be developed with different panel densities, and generally less intensive designs will be more easily accepted locally. However, lower densities also significantly reduce average electricity production per ha, thereby requiring more land for the same production quantity. This element should be part of the policy discussion on land-based PV park designs.

If PV projects make use of the most efficient PV panels available on the market at their time of realisation, instead of the most cost-effective ones, the required area for meeting the same amount of electricity production is reduced significantly. Policy makers should bear this in mind when designing support schemes for PV and could also consider including an incentive for using more efficient systems, or generally making more efficient use of space.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Jan Matthijsen (PBL), Martin Tillema and Sjoerd Radersma (both Kadaster land registry) for their valuable support in designing the methodology and using the spatial databases. Bob Meijer (TKI Offshore Wind) assisted with the assumptions on offshore solar parks. We also thank the many policy makers that helped shape our analytical framework and the many assumptions.

This work was partially funded by the Ministry of Economic Affairs and Climate, through their basic funding of TKI Urban energy.

References

- Abreu, J., Wingartz, N., Hardy, N., 2019. New trends in solar: A comparative study assessing the attitudes towards the adoption of rooftop PV. *Energy Policy* 128, 347–363. <https://doi.org/10.1016/j.enpol.2018.12.038>.
- Anonymous, 2018. State of the State-onderzoek: Zonnepanelen kunnen de helft van de Nederlandse elektriciteitsbehoefte opwekken (State of the State research: solar panels can generate half of Dutch electricity demand). Deloitte, S.I.
- Anonymous, 2019a. Predictions for the PV industry in 2019. IHS markit, S.I.
- Anonymous, 2019b. International Technology Roadmap for Photovoltaic (ITRPV); 2018 Results. ITRPV and VDMA, Frankfurt am Main.
- Anonymous, 2019c. Klimaatakkoord (Climate Agreement). Den Haag.
- Anonymous, 2020a. Basisregistratie Adressen en Gebouwen - BAG (Base Registration Addresses and Buildings) [WWW Document]. Kadaster. URL <https://www.kadaster.nl/zakelijk/registraties/basisregistraties/bag>.
- Anonymous, 2020b. Esri Woningtypekaart (Esri Map of Dwelling Types) [WWW Document]. URL <https://www.arcgis.com/home/item.html?id=283f14dcd39448bd929461d2725be5cb> (accessed 2.20.20).
- Anonymous, 2020c. 3D Basisregistratie Adressen en Gebouwen (BAG) (3D Base Registration Addresses and Buildings) [WWW Document]. URL <http://3dbag.bk.tudelft.nl/> (accessed 10.15.20).
- Anonymous, 2020d. PVGIS (PV-GIS) [WWW Document]. URL https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP.
- Anonymous, 2021a. Zonopinfra [WWW Document]. URL <https://zonopinfra.nl/home>.
- Anonymous, 2021b. Solaroad [WWW Document]. URL <https://www.solaroad.nl/>.
- Brand, A., Roozendaal, J., Peppelman, M., Wind, T., 2017. Vormfactoren & Kostenkenngetallen Assets (Shape Factors & Cost Indicators Assets). Arcadis, Arnhem.
- Carlisle, J.E., Kane, S.L., Solan, D., Bowman, M., Joe, J.C., 2015. Public attitudes regarding large-scale solar energy development in the U.S. *Renewable and Sustainable Energy Reviews* 48, 835–847. <https://doi.org/10.1016/j.rser.2015.04.047>.
- Carlisle, J.E., Kane, S.L., Solan, D., Joe, J.C., 2014. Support for solar energy: Examining sense of place and utility-scale development in California. *Energy Res. Social Sci.* 3, 124–130. <https://doi.org/10.1016/j.erss.2014.07.006>.
- CBS, 2020. *Hernieuwbare energie in Nederland 2019* (Renewable Energy in the Netherlands 2019). Central Bureau of Statistics, The Hague.
- CBS, 2021. Productie groene stroom met 40 procent gestegen (generation green electricity raised by 40 percent) [WWW Document]. accessed 5.20.21. <https://www.cbs.nl/nl-nl/nieuws/2021/08/productie-groene-stroom-met-40-procent-gestegen>.
- CBS, 2018. Bestand Bodemgebruik 2015 (Datafile Land Use 2015) [WWW Document]. URL <https://www.nationaalgeoregister.nl/geonetwork/srv/api/records/2d3dd6d2-2d2b-4b5f-9e30-86e19ed77a56> (accessed 10.20.20).
- Centeno Brito, M., Santos, T., Moura, F., Pera, D., Rocha, J., 2021. Urban solar potential for vehicle integrated photovoltaics. *Transp. Res. Part D: Transport and Environ.* 94, 102810. <https://doi.org/10.1016/j.trd.2021.102810>.
- de Jager, D., Staats, M., Hofsteenge, W., Nouthout, P., 2017. Overig hernieuwbare energie in Nederland; een potentieel studie (Other renewable energy in the Netherlands; a potential study). Ecofys, Utrecht.
- Defaix, P.R., van Sark, W.G.J.H.M., Worrell, E., de Visser, E., 2012. Technical potential for photovoltaics on buildings in the EU-27. *Sol. Energy* 86 (9), 2644–2653. <https://doi.org/10.1016/j.solener.2012.06.007>.
- Den Ouden, B., Kerkhoven, J., Warnars, J., Terwel, R., Coenen, M., Verboon, T., 2020. Klimaatneutrale energiescenario's 2050; Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030–2050 (Climate neutral energy scenarios 2050; scenario study for the integral infrastructure outlook 2030–2050). Berenschot/Kalavasta, Utrecht.
- DNE research, 2021. National Solar Trend Report 2021. DNE Research, S.I.
- Dupont, E., Koppelaar, R., Jeanmart, H., 2020. Global available solar energy under physical and energy return on investment constraints. *Appl. Energy* 257, 113968. <https://doi.org/10.1016/j.apenergy.2019.113968>.
- Engelken, M., Römer, B., Drescher, M., Welp, I., 2018. Why homeowners strive for energy self-supply and how policy makers can influence them. *Energy Policy* 117, 423–433. <https://doi.org/10.1016/j.enpol.2018.02.026>.
- Environmental Data Compendium, 2020. Land use in the Netherlands, 2015 [WWW Document]. URL <https://www.clo.nl/en/indicators/en0061-land-use-in-the-netherlands>.
- Folkert, R., van den Wijngaart, R., 2012. VESTA ruimtelijk energiemodel voor de gebouwde omgeving; Data en methoden (VESTA spatial energy model for the built environment; Data and methods). Planbureau voor de Leefomgeving, The Hague.
- Folkerts, W., Sark, W., van Keizer, C. de, Hooft, W. van, Donker, M. van den, 2017. ROADMAP PV Systemen en Toepassingen (ROADMAP PV Systems and Applications). SEAC, Utrecht University and TKI Urban Energy, S.I.
- Frankfurt School, UNEP, Bloomberg NEF, 2020. Global Trends in Renewable Energy Investment 2020. Frankfurt School of Finance & Management, Frankfurt am Main.
- Gernaat, D.E.H.J., de Boer, H.S., Dammeier, L.C., van Vuuren, D.P., 2020. The role of residential rooftop photovoltaic in long-term energy and climate scenarios. *Appl. Energy* 279, 115705. <https://doi.org/10.1016/j.apenergy.2020.115705>.
- Golroodbari, S.Z., van Sark, W., 2020. Simulation of performance differences between offshore and land-based photovoltaic systems. *Prog. Photovoltaics Res. Appl.* 28, 873–886. <https://doi.org/10.1002/ppp.3276>.
- Guaita-Pradas, I., Marques-Perez, I., Gallego, A., Segura, B., 2019. Analyzing territory for the sustainable development of solar photovoltaic power using GIS databases. *Environ. Monit. Assess.* 191 <https://doi.org/10.1007/s10661-019-7871-8>.
- Hong, T., Yoo, H., Kim, J., Koo, C., Jeong, K., Lee, M., Ji, C., Jeong, J., 2017. A model for determining the optimal lease payment in the solar lease business for residences and third-party companies-With focus on the region and on multi-family housing complexes. *Renew. Sustain. Energy Rev.* 82, 824–836. <https://doi.org/10.1016/j.rser.2017.09.068>.
- Hoogwijk, M.M., 2004. On the global and regional potential of renewable energy sources. Utrecht University, Utrecht. PhD Thesis.
- Iea, 2020a. World Energy Outlook 2020. International Energy Agency, Paris.
- IEA, 2020b. Renewable energy market update. International Energy Agency, Paris.
- IEA, 2021. Net zero by 2050; a roadmap for the global energy sector. International Energy Agency, Paris.
- IEA-PVPS, 2021. Snapshot of global PV markets. International Energy Agency, Photovoltaic Power Systems Programme, S.I.
- International Electrotechnical Commission, n.d. IEC 60904:2020 Photovoltaic devices [WWW Document]. URL <https://webstore.iec.ch/publication/3881>.
- IPCC, 2011. *Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge.
- IRENA, 2018. Global energy transformation; a roadmap to 2050. International Renewable Energy Agency, Abu Dhabi.
- IRENA, 2020. Global Renewables Outlook 2050: Energy Transformation. Edition 2020. International Renewable Energy Agency, Abu Dhabi.
- Jamil, M., Rizwan, M., Kothari, D.P., 2017. *Grid Integration of Solar Photovoltaic Systems*. CRC Press, S.I.
- Janssen, G.J.M., Van Aken, B.B., Carr, A.J., Mewe, A.A., 2015. Outdoor Performance of Bifacial Modules by Measurements and Modelling, in: *Energy Procedia*. Elsevier Ltd, pp. 364–373. <https://doi.org/10.1016/j.egypro.2015.07.051>.
- Kadaster, 2020. Basisregistratie Grootchalige Topografie (Base Registration Large-Scale Topography) [WWW Document]. URL <https://www.kadaster.nl/zakelijk/registraties/basisregistraties/bgt> (accessed 10.15.20).
- Kaldellis, J.K., Kapsali, M., Kaldelli, E., Katsanou, E., 2013. Comparing recent views of public attitude on wind energy, photovoltaic and small hydro applications. *Renewable Energy* 52, 197–208. <https://doi.org/10.1016/j.renene.2012.10.045>.
- Kuijers, T., Hocks, B., Witte, J., Becchi, F., Wijnakker, R., Frijters, E., Zeif, S., Hugtenburg, J., Veul, J., Meeuwssen, A., Sijmons, D., Vermeulen, M., Willemse, B., Stremke, S., Oudes, D., Boxmeer, B. van, Knuivers, R., Vries, S. de, 2018. KLIMAAT ENERGIE RUIMTE; Ruimtelijke verkenning energie en klimaat (CLIMATE ENERGY SPACE; Spatial exploration energy and climate). Posad, FABRICations, H+N+S, Sijmons, Studio Marco Vermeulen, WUR, Ruimtevolk, S.I.

- Lang, T., Ammann, D., Girod, B., 2016. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renewable Energy* 87, 77–87. <https://doi.org/10.1016/j.renene.2015.09.059>.
- Lemmens, J., van der Burgt, J., Bosma, T., van den Wijngaart, R., van Bommel, B., Koelemeijer, R., 2014. Het potentieel van zonnestroom in de gebouwde omgeving van Nederland (The potential of solar power in the built environment of the Netherlands). PBL/DNV-GL, The Hague/Arnhem.
- Londo, M., Kramer, G.J., 2019. Ruimtelijke opgaven door klimaatbeleid (Spatial challenges by climate policy). *Landschap* 36, 189–197.
- Londo, M., Matton, R., Usmani, O., van Klaveren, M., Tigchelaar, C., Brunsting, S., 2020. Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental costs. *Renewable Energy* 147, 903–915. <https://doi.org/10.1016/j.renene.2019.09.062>.
- Lupangu, C., Bansal, R.C., 2017. A review of technical issues on the development of solar photovoltaic systems. *Renew. Sustain. Energy Rev.* 73, 950–965. <https://doi.org/10.1016/j.rser.2017.02.003>.
- MacKay, D.J., 2009. Sustainable Energy - without the hot air. UIT Cambridge Ltd., Cambridge.
- Manders, T., Kool, C., 2015. Nederland in 2030 en 2050: twee referentiescenario's. Toekomstverkenning welvaart en leefomgeving (The Netherlands in 2030 and 2050: two reference scenarios. Outlook on welfare and living environment). PBL/CPB, The Hague.
- Mavsar, P., Sredenssek, K., Štumberger, B., Hadžiselimović, M.H., Seme, S., 2019. Simplified Method for Analyzing the Availability of Rooftop Photovoltaic Potential. *Energies* (Basel) 12. <https://doi.org/10.3390/en12224233>.
- Mayer, J.N., Philipps, S., Hussein, N.S., Schlegel, T., Senkpiel, C., 2015. Current and Future Cost of Photovoltaics; Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study for Agora Energiewende. Fraunhofer ISE, S.I.
- Moratis, P., Sark, W.G.J.H.M. van, 2014. Operational performance of grid-connected PV systems. 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC) 1953–1956. <https://doi.org/10.1109/PVSC.2014.6925308>.
- PBL, TNO, CBS, RIVM, 2020. Klimaat- en Energieverkenning 2020 (Climate and Energy Outlook 2020). Planbureau voor de Leefomgeving, The Hague.
- Perpina Castillo, C., Batista e Silva, F., Lavalie, C., 2016. An assessment of the regional potential for solar power generation in EU-28. *Energy Policy* 88, 86–99. <https://doi.org/10.1016/j.enpol.2015.10.004>.
- Quintel Intelligence, 2020. Energy Transition Model [WWW Document]. URL <https://docs.energytransitionmodel.com/main/intro/> (accessed 10.14.20).
- Reich, N.H., Mueller, B., Armbruster, A., Van Sark, W.G.J.H.M., Kiefer, K., Reise, C., 2012. Performance ratio revisited: is PR > 90% realistic? Progress in Photovoltaic Research and Applications 20, 717–726. <https://doi.org/10.1002/ppp.1219>.
- Romijn, I., 2017. Bifacial PV – now and in the future; presentation on Sunday Conference. Bussum.
- Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B.S., Brosowski, A., Thrän, D., 2019. ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews* 26. <https://doi.org/10.1016/j.esr.2019.100379>.
- RVO, 2021. SDE(+) projecten in beheer (januari 2021) (SDE(+) projects in portfolio (January 2021)). Rijksdienst voor Ondernemend Nederland, Utrecht.
- Scheepers, M., Faaij, A., Brink, R. van den, 2020. Scenario's voor klimaatneutraal energiesysteem; Slimme combinaties van energie-opties leiden tot duurzame en betaalbare energiehuishouding (Scenarios for climate neutral energy system; smart combinations of energy options lead to sustainable and affordabl. TNO, Petten.
- Schotman, A., Zee, F. van der, Hazeu, G., Bloem, J., Sluijsman, J., Vittek, M., 2021. Verkenning van bodem en vegetatie in 25 zonneparken in Nederland (exploration of soil and vegetation in 25 solar parks in the Netherlands). Wageningen Environmental Research, Wageningen.
- Shell, 2018. Shell scenarios: Sky; Meeting the goals of the Paris agreement. Shell International, S.I.
- Sijmons, D., 2008. Kleine energieatlas. Ruimtebeslag van elektriciteitsopwekking (Small Energy Atlas; Spatial Claims of Electricity Production). Ministerie van VROM, Den Haag.
- Sijmons, D., FABRICations, H+N+S Landschapsarchitecten, Strategies, P. spatial, Studio Marco Vermeulen, NRGlab/Wageningen Universiteit, Vereniging Deltametropool, 2017. Energie en Ruimte; een national perspectief (Energy and Space; a national perspective). Vereniging Deltametropool, S.I.
- Sinapis, K., Tsatsakis, K., Dörenkämper, M., van Sark, W.G.J.H.M., 2021. Evaluation and Analysis of Selective Deployment of Power Optimizers for Residential PV Systems. *Energies* (Basel) 14, 811. <https://doi.org/10.3390/en14040811>.
- Sinke, W., van Hooff, W., Romijn, I., Kroon, J., Newman, B., Weeber, A., 2016. xSi PV technologies roadmap. ECN and TKI Urban Energy, Petten/Utrecht.
- Sommerfeld, J., Buys, L., Vine, D., 2017. Residential consumers' experiences in the adoption and use of solar PV. *Energy Policy* 105, 10–16. <https://doi.org/10.1016/J.ENPOL.2017.02.021>.
- Uyterlinde, M., Londo, M., Sinke, W., van Roosmalen, J., Eecen, P., van den Brink, R., Stremke, S., van den Brink, A., de Waal, R., 2017. De energietransitie: een nieuwe dimensie in ons landschap (The energy transition: a new dimension in our landscape). ECN/WUR, Petten/Wageningen.
- Ham, A. van der, 2019. PV in mobility, presentation on Sunday 2019. Bussum.
- van Druten, E., Kruit, K., 2019. Perspectieven elektriciteit uit water; Nationaal potentieel voor 2030 en 2050 (Perspectives electricity from water; national potential for 2030 and 2050). Witteveen+Bos and CE Delft, Deventer.
- van Hooff, W., Sinke, W., 2019. Hernieuwbare elektriciteitsopwekking op land en de gebouwde omgeving (MMIP 2); Meerjarig Missiegedreven Innovatieprogramma (Renewable electricity generation on land and in the built environment (MMIP2); Multi-annual Mission-driven Innovation Programme). TKI Urban Energy, Utrecht.
- van Hooff, W., Kuijers, T., Quax, R., Witte, J., 2021. Ruimtelijk potentieel van zonnestroom in Nederland (Spatial potential of solar power in the Netherlands). TKI Urban Energy, Utrecht.
- Van Puijenbroek, P.J.T.M., Clement, J., n.d. Basiskaart Aquatisch: de Watertypenkaart. Het oppervlaktewater in de TOP10NL geclassificeerd naar watertype (Base Map Aquatic: the Map of Water Types. Surface water in the TOP10NL classified to water type). PBL, The Hague.
- Veenstra, A., 2015. Ruimte voor zonne-energie in Nederland 2020–2050; Analyse van ruimtelijke groeikansen en knelpunten voor zonne-energie toepassingen in Nederland (Space for solar energy in the Netherlands 2020–2050; Analysis of spatial growth opportunities and challenges). Holland Solar, Utrecht.
- Wiebes, E., 2021. Verloop openstelling SDE++ 2020; Kamerbrief (Course opening SDE++ 2020; Letter to the Parliament). Ministry of Economic Affairs and Climate, The Hague.