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The role of residential rooftop photovoltaic in long-term energy and climate scenarios

David E.H.J. Gernaat[a,b,*], Harmen-Sytze de Boer[a,b], Louise C. Dammeier[a,c], Detlef P. van Vuuren[a,b]

[a] *PBL Netherlands Environment Assessment Agency, Bezuidenhoutseweg 30, 2594 AV Den Haag, the Netherlands*
[b] *Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8, 3584 CB Utrecht, the Netherlands*
[c] *Department of Environmental Science, Radboud University, Heyendaalseweg 135, 6525 AJ Nijmegen, the Netherlands*

HIGHLIGHTS

- Rooftop PV key driver in the PV market, thus modelled in IMAGE IAM.
- Global estimated potential 8.3 PWh y^{-1}: 1.5 times residential electricity demand.
- Scenarios show key role for rooftop PV but regional characteristics crucial.
- Income levels and grid electricity prices dominate regional deployment.
- Low-irradiation western Europe better than high-irradiation Middle East.

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ABSTRACT

The use of solar photovoltaic has strongly increased in the last decade. A significant part of this growth comes from home owners installing rooftop photovoltaic. Despite this key role, most long-term model-based scenarios do not consider decentralized supply of rooftop photovoltaic but concentrate on utility-scale photovoltaic instead. In this paper, we implement rooftop photovoltaic in the Integrated Assessment Model IMAGE to study its possible role in energy and climate scenarios. We first calculated the global technical and economic potential to derive regional cost-supply curves for rooftop photovoltaic. Next, we have added a new decision in the IMAGE model allowing household investment in rooftop photovoltaic based on the comparison of the whole-sale electricity price with the price of rooftop photovoltaic. The global suitable roof surface area was assessed at 36 billion m^2, or 4.7 m^2 $capita^{-1}$, leading to a potential for rooftop photovoltaic of 8.3 PWh y^{-1}, roughly 1.5 times the 2015 global residential electricity demand. In the baseline scenario, adding rooftop photovoltaic could lead to a 80–280% increased share of photovoltaic electricity production in 2050 (i.e. from 6% to 17% in total power production). This increase depends on regional characteristics that are essential to the deployment of rooftop photovoltaic: differences in social-economic and policy factors (capital costs, household income, and electricity prices) are considerably more important than physical factors, such as solar irradiance.

1. Introduction

The use of solar photovoltaic (PV) has strongly increased in the last decade. The capacity increased from 6.6 GW to over 500 GW in the 2006–2018 period [1]. Interestingly, the main driver for this development were investments done by home owners in rooftop PV, not investments in utility-scale PV [2,3]. In fact, rooftop PV accounts for the majority of installed capacity today [2]. One reason for this is that home owners perceive the costs of PV differently than utilities. Utilities compare the costs of PV with the whole-sale electricity market with competitive price levels of around 0.03–0.05 \$ kWh^{-1}, currently supplied by coal and gas-fired power plants. Home owners, however, compare the costs of rooftop PV with electricity retail prices. These prices are, in general, considerably higher than electricity market prices because of taxes, and transmission and distribution (T&D) costs. Home owners can also benefit from subsidies and net-metering. The latter is a

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* Corresponding author.
E-mail address: david.gernaat@pbl.nl (D.E.H.J. Gernaat).

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Table 1

Regional capital costs in 2015 (\$ kW^{-1}) that were used in this study. Regular font is directly based on IEA [20], italic font indicates the allocation of IEA data to another IMAGE region. Prices were further checked to more recent cost numbers [20], see Appendix, Table A4 for regional capital cost generated by the IMAGE model.

IEA region	IMAGE region	Utility-scale PV	Additional cost for rooftop PV	Rooftop PV O&M
Europe	Western Europe	1320	280	16
Europe	Central Europe	1320	280	16
United States	US	2220	1260	34
United States	Canada	*2220*	*1260*	34
United States	Oceania	*2220*	*1260*	*34*
Japan	Japan	2020	860	28
Japan	Korea	*2020*	*860*	*28*
Russia	Russia	2580	900	34
Russia	Turkey	*2580*	*900*	*34*
Russia	Ukraine	*2580*	*900*	*34*
Russia	Central Asia	*2580*	*900*	*34*
China	China +	1360	120	14
China	Southeastern Asia	*1360*	*120*	*14*
China	Indonesia	*1360*	*120*	*14*
China	Rest of south Asia	*1360*	*120*	*14*
India	India +	1340	120	14
Middle East	Middle East	2360	640	30
Africa	Northern Africa	2400	440	28
Africa	Western Africa	2400	440	28
Africa	Eastern Africa	2400	440	28
Africa	Southern Africa	2400	440	28
Africa	Rest of southern Africa	2400	440	28
Brazil	Brazil	1980	700	30
Brazil	Mexico	*1980*	*700*	*30*
Brazil	Rest of Central America	*1980*	*700*	*30*
Brazil	Rest of South America	*1980*	*700*	*30*

policy instrument allowing home-owners to sell excess electricity to the grid at retail price. Net-metering is, for instance, allowed in several states in the US and some European countries to incentivize rooftop PV investments [4]. The competitive position of PV thus not only depends on differences in solar irradiation, but also on these regional factors such as retail electricity prices, taxes, policies, and capital cost. This is, for instance, clearly shown by Lang [5] indicating that PV can be more attractive in a low-irradiation country like Germany than a high-irradiation country like Qatar. The same was demonstrated comparing Germany with California [6,7].

Scenarios developed by Integrated Assessment Models (IAMs) are used to inform policy makers on choices regarding energy and climate issues. Given the importance of rooftop PV in the past, one might expect that IAM scenarios would include an adequate description of its dynamics. Most IAM scenarios, however, do not consider rooftop PV but concentrate on utility-scale PV instead [8–11]. In this paper, we aim to develop an estimate of the economic potential of rooftop PV, and implement this technology in an IAM to study its possible role in long-term energy and climate scenarios. For this, we derived regional cost-supply curves for rooftop PV and used these curves to create a rooftop PV technology in the IMAGE IAM. The possibility for households to decide for rooftop PV was modelled trough a new investment decision that compares the whole-sale electricity price with the price of rooftop PV. This decision was implemented with region specific characteristics, such as income levels, retail electricity prices, taxes, and investment levels. For the latter, the Shared Socio-economic Pathways (SSPs) scenarios, as implemented in IMAGE, were used to explore long-term development [12].

2. Methods

In order to estimate the economic potential for rooftop PV and implement this in IMAGE, several steps were taken that are explained in the sections below. First, we assessed the technical potential of rooftop PV based on residential roof area (see Section 2.1.1). Next, we combined the technical potential with economic information to derive cost-supply curves (see Section 2.1.2). Subsequently, we estimated the role of solar rooftop PV in future energy systems using the IMAGE model (see Section 2.2) and the SSP scenarios (see Section 2.3). For a schematic representation of the methodology see the flow chart in Appendix, Fig. A1.

2.1. Cost-supply curves of rooftop PV

2.1.1. Technical potential of rooftop PV

We use Eq. (1) to calculate the potential annual electricity from rooftop surfaces (E_{rt}) (kWh y^{-1}):

$$E_{rt} = G \cdot \eta \cdot PR \cdot SRA \tag{1}$$

where G is the solar irradiation based on the NASA SSE6 Global Horizontal Radiation dataset available in 0.5° × 0.5° (kWh m^{-2} y^{-1}), η is the panel efficiency, PR is the performance ratio expressing the difference between performance under standard test conditions the actual output of the system due to losses from sub-optimal angles and cable or inverter losses, and SRA the suitable roof area (see Eq. (2)). For the panel efficiency, 17% is chosen to represent modern crystalline Silicon panels [13,14]. A PR of 85% is chosen to reflect increasing capacity factors of recent years [13,14]. Data for roof area (SRA) is harder to obtain, as a global dataset does not exist. Instead, we have used estimates for floor space, in combination with census data on the number of floors per household (Eq. (2)). Daioglou [15] identified a relationship between floor space and household expenditures. According to this, floor space is linearly related to household expenditures, while population density logarithmically decreases floor space. The relationship distinguishes between urban and rural households, allowing for larger floor spaces in rural households despite lower household expenditures. This function (see Eq. (2), second part) was calibrated on available statistical data from the WorldBank [16] ($R^2 = 0.67$). We used the following equation to convert floor space into roof area per household h, per region r (Appendix, Fig. A2 for IMAGE regions), per division (urban/ rural) i:

$$SRA_{h,r,i} = F_{h,r,i} \cdot \beta_r \cdot S = (x_1 \cdot \ln(PD_r) + x_2) \cdot (1 + \frac{\alpha \cdot HE_r}{35000}) \cdot e^{-\varphi_2 e^{-\left(\frac{\varphi_3}{1000}\right)}}) \cdot (x_3 \cdot U_r + x_4) \cdot \beta_r \cdot S \tag{2}$$

where $SRA_{h,r,i}$ is the suitable roof area (m^2), $F_{h,r,i}$ is the floor space (m^2) as calculated by Daioglou [15], β_r is the coefficient that converts floor space into roof area, and S is the coefficient that converts roof area into suitable architecturally available area for PV (0.32, see below for a further description). Floor space itself ($F_{h,r,i}$) was calculated as described by the second part of Eq. (2) [17], where x_1 is −2.964, PD_r is the population density (capita km^{-2}), x_2 is 60.577, α is 0.125, HE_r is household expenditure ($ household^{-1}), ϕ_2 is 1.341, ϕ_3 is 0.125, x_3 is 0.289 and U_r is the population division factor (urban/rural) and x_4 is 0.717.

The β coefficient is based on the number of floors per household. A household with three floors (ground floor, 1st floor, and 2nd floor), for example, has a β coefficient of 0.33 because the roof area equals a third of the floor space. The number of floors were taken from census data available for twenty countries that cover eleven IMAGE regions (see Appendix, Table A1). For the remaining regions, we estimated a coefficient based on the resemblance with other regions. This way we matched, for example, Canada to the US (see Appendix, Tables A2 and A3). In other cases, we used the global average. The β coefficients show clear regional differences. The US, for example, have a β coefficient of 0.46, reflecting a low-rise building style. In contrast, the β of Japan (0.3), reflects a high-rise building style. The available roof area thus differs depending on cultural characteristics. We assume these characteristics to stay the same in our scenario analyses (an assumption further discussed in Section 4).

The total rooftop area was multiplied by a suitability coefficient (S in Eq. (2)) to account for roof types (flat or tilted), shading, orientation, and architectural obtrusions. Based on a study that used high-resolution satellite data to assess available roof area in the US [18] this number was chosen to be 0.32. Due to lack of data we could not implement regional differentiation (an assumption further discussed in Section 4).

The regional roof areas were scaled down to a 0.5° × 0.5° global map based on geographic population data to distinguish between rural and urban population [19]. This roof area map was combined with the solar irradiation data to obtain the annual technical potential of rooftop PV per grid cell.

2.1.2. Costs of rooftop PV

The levelized costs for rooftop PV (LCOE) ($ kWh^{-1}) were calculated at the 0.5° x 0.5° grid using the following equation per grid cell i and per region r:

$$LCOE_i = \frac{ann\cdot(I_r + \varepsilon_r)\cdot y_r + ann\cdot(I\_RT_r + \varepsilon\_RT_r)\cdot y\_RT_r}{E_i} \quad (3)$$

where ann is the annuity factor (20 year lifetime, 10% discount rate), I_r are the regional investment costs for utility scale PV ($ kW^{-1}), ε_r are the O&M costs for utility scale PV ($ kW^{-1}), γ_r is the technology improvement of utility-scale PV (see Eq. (4)), I_RT_r and ε_RT_r are the additional costs for rooftop PV ($ kW^{-1}), γ_r is the technology development of rooftop PV (see Eq. (4)), and E_i is the electricity produced in the grid cell (see Eq. (1)). For utility-scale PV costs (I_r and ε_r), we used data on capital costs from the IEA [20] resulting in regional costs ranging from 1320 $ kW^{-1} in Europe to 2580 $ kW^{-1} in Russia (see Table 1). Additional costs to install rooftop PV (I_RT_r and ε_RT_r) on residential roofs were also based on IEA [20] (Table 1) and range from 120 $ kW^{-1} in China to 1260 $ kW^{-1} in the US; as were operation and maintenance (O&M) costs. See Appendix, Table A4, for regional technical details.

The large variations in regional capital costs have various reasons. Firstly, some regions, such as the US, have trade barriers protecting domestic industries. Secondly, some regions are more experienced than others in the installation of PV systems. Europe, for example, has had an active PV industry in the last decade but this is less for other regions, such as the US. Exchanging knowledge with trading PV panels is easy, but transferring experience on installation skills is difficult. Thirdly, some regions, such as China, are producers of PV panels while others, such as Africa, are importers. Finally, developing regions have lower wages compared to developed regions resulting in lower production and installation cost. As these differences in costs clearly exist, it is important to include them in the model.

In the future we expect these regional capital costs to converge due to learning effects, information sharing, and trade. In our default scenarios, we assume convergence of costs, for both utility-scale and rooftop PV, to European levels within approximately ten years (2025). We chose European cost levels (280 $ kW^{-1} additional cost for rooftop PV) over Chinese and Indian levels (120 $ kW^{-1}) due to the expected rise of labour costs in China and India. Lastly, in our long-term scenario, we assume a floor cost of 150 $ kW^{-1} to prevent utility-scale PV costs going to near-zero.

The costs for both utility-scale PV and rooftop PV declined 40–75% between 2010 and 2015 [1,2,20,21]. For technology development, we applied a so-called learning curve that assumes that costs decrease endogenously as a function of the cumulative energy capacity as indicated in Eq. (4):

$$\gamma = \alpha Q^{-\pi} \quad (4)$$

where π is the learning rate (20%), Q the cumulative capacity, and α is the cost of the first unit produced. The learning rate, often indicated as the progress ratio, indicates how fast costs decrease with a doubling of cumulative capacity (progress ratio = $2^{-\pi}$).

The historical trend fits a historical learning rate of 20% (see Appendix, Table A4). This rate we also used for future scenarios for both direct costs for PV modules and additional costs for the rooftop PV system. The costs for the PV system are increasingly determined by non-module cost, such as support, cables, or inverters. There is, however, little evidence that the non-module part has a different learning rate. In fact, there is more evidence for similar learning rates [22–24].

Finally, the annual information of technical potential and costs are calculated at 0.5° × 0.5° grid. The data is subsequently converted in cost-supply curves per IMAGE regions by sorting, from low to high, the grid cells on costs, while simultaneously adding the same cells from the technical potential map (see Appendix, Fig. A2 for the IMAGE regions).

2.2. Implementation of rooftop PV in IMAGE

2.2.1. IMAGE integrated assessment model

We use the cost-supply curves in IMAGE to study the long-term role of rooftop PV in future energy system. IMAGE has been developed to study global environmental change by describing the key interactions between humans and the environment. Within IMAGE, the energy-system model TIMER describes the energy system for 26 world regions in terms of energy demand and energy supply. Energy demand starts from the energy services that generate energy use, such as transportation, heating, or lighting. The demand for services is based on economic activities. These are modelled in detail in some cases (e.g. residential sector) but in other cases they are derived directly from changes in GDP. The demand for energy can be fulfilled by various energy carriers. Choosing between these carriers depends on relative prices and preferences. By correcting for end-use efficiencies, the demand for secondary energy (e.g. electricity, gasoline, or hydrogen) is derived, which is subsequently supplied by primary energy carriers that undergo several conversions steps; electricity demand, for example, is based on the underlying demand for fossil fuels, nuclear power, and renewables.

The long-term costs of primary energy carriers are based on technology development and resource depletion. Technological development is implemented in the form of learning curves, decreasing the cost over time as more is used. Resource costs, however, increase as they get depleted, which is modelled with the cost-supply curve information (such as derived for rooftop PV in 2.12). Below, we describe methods used to estimate rooftop PV cost-supply curves and how these cost-supply curves are implemented in IMAGE [25]. The use of rooftop PV

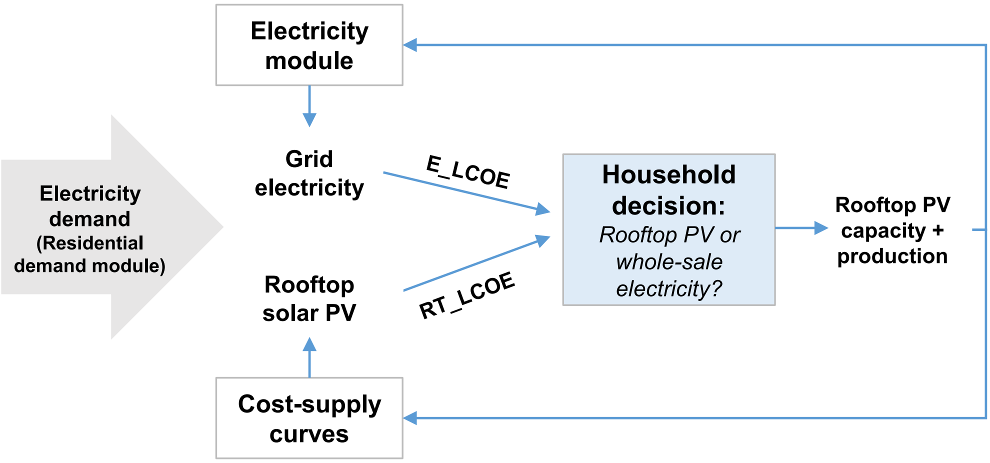

Fig. 1. Schematic representation of the rooftop PV modelling (see Appendix, Fig. A3 for a more complex representation; see Eq. (6) for definition E_LCOE and RT_LCOE).

is determined in the residential energy demand model, where it competes with grid-based electricity.

2.2.2. *Grid-based electricity*

The electricity module simulates the generation of 28 different combinations of renewable, nuclear, fossil-fuel, and bio-energy technologies. It is described in detail in the Appendix, Text A1. The 28 technologies compete for market-shares in the supply of electricity based on relative costs and additional system factors for reliability requirements. The electricity price is calculated based on the costs of the resulting system [26].

2.2.3. *The use of rooftop PV*

The residential energy-demand module describes the energy choices made by households for heating, cooling, cooking, lighting, and appliances (see Appendix, Fig. A3 for a schematic representation from Daioglou [15]). The model distinguishes between urban and rural households, each represented by five income groups. Several physical and economic drivers, such as population density, income levels, temperature, and floor space, are involved to calculate the demand for these end-use energy services.

The fuel choice is based on the perceived costs of various alternatives. Here, income levels play a key role. Low-income groups have lower liquidity and difficult access to loans; high-income groups, however, have higher liquidity and easier access to loans. High-income groups are therefore more likely to make long-term investments. These different behaviours are described with consumer discount rates (CDRs): a high discount rate for low-income groups and a low one for high-income groups. Empirical evidence indicates that CDRs can be as high as 80% for low-income groups but as low as 10% for high-income groups [27,28]. In the residential energy-demand module, the CDRs depend on household expenditures and are described by Eq. (5) per region r, per division (urban/ rural) i, per income quintile j:

$$CDR_{r,i,j} = x_1 + e^{x_2 - x_3 \cdot HE_{r,i,j}} \tag{5}$$

where x_1 is 10, x_2 is 6.902, x_3 is 0.008 and $HE_{r,I,j}$ is the household expenditure (\$ household^{-1}) based on data from WorldBank [16].

In IMAGE, we apply this equation to the five different income groups per region for urban and rural population. The costs of fuel alternatives for each income group are subsequently calculated using the discount rates. Given the difference in investment costs for various fuel alternatives, the emergent behaviour leads to trends that represent the energy ladder (fuel switching behaviour from fuels with low-investment costs, such as wood, to modern fuels with high-investment costs, such as electricity) [29]. The relative costs are also influenced by additional price factors such as taxes, subsidies, and distribution costs. Data on these components are based on Jewell [30].

A new decision was implemented in the model that determined whether a household buys whole-sale electricity from the grid, or invests

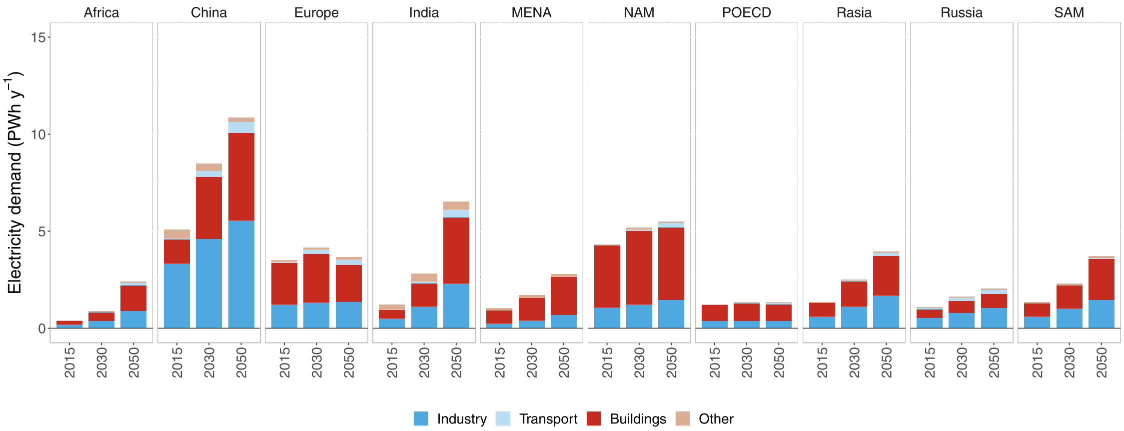

Fig. 2. Regional electricity demand per sector for the SSP2 baseline scenario. The electricity demand from buildings is the sum of the services sector and the residential sector. (MENA = Middle East and north Africa, NAM = North America, POECD = Pacific OECD, RAsia = Rest of Asia (Asia excluding India and China), SAM = South America).

Table 2
Scenarios used in this study. See Appendix, Text A2 and Figs. A4, A5 for a detailed explanation of the SSP scenarios.

Scenario name	Abbreviation	Explanation
Baseline without rooftop PV	SSP2	SSP2 baselines, no climate policy, without rooftop PV
Baseline with rooftop PV	SSP2_RT	SSP2 baseline, no climate policy, with rooftop PV but without net-metering policy
Rooftop PV Policy	SSP2_RTPol	SSP2 baseline, no climate policy, with rooftop PV and net-metering policy
Climate policy without rooftop PV	SSP2_ClimPol	SSP2 with radiative forcing target of 2.6 W m^{-2} in 2100, without rooftop PV and net-metering policy
Climate policy with rooftop PV	SSP2_RTPol_ClimPol	SSP2 with radiative forcing target of 2.6 W m^{-2} in 2100, with rooftop PV and net-metering policy

Table 3
Comparing calculated roof areas and technical potentials to literature.

Region	Source	Suitable roof area (km^2)	Technical potential (TWh y^{-1})
Global	Hoogwijk et al. (2004)	150,000	6000
	This study	36,237	8310
Global	Deng [35]	40,000	8611
	This study	36,237	8310
Global urban	OECD/IEA [39]	25,000	5800
	This study	18,550	4161
US	Gagnon et al. (2016)	4950	926[1]
	This study	2637	591
EU	Defaix et al. (2014)	3678	840[2]
	This study	4015	705
Spain	Izquierdo [37]	571	42
	This study	950[3]	71
Switzerland	Assouline [38]	328	18
	This study	126[3]	7

[1] Only the small building class (<5000 ft^2).

[2] The total potential Defaix et al. (2012) is 840 TWh y^{-1}, this includes commercial buildings and facades. Subtracting the commercial area (1301 km^2, 24% of total surface) reduces the potential to 620 TWh y^{-1}. There are also mismatches on countries compared to the numbers in calculated in this article. The numbers of this study are calculated with EU defined as IMAGE regions western Europe and eastern Europe.

[3] Does not include the suitability coefficient (S in Eq. (2); 0.32) to improve comparability with the reference.

in rooftop PV (see Fig. 1).

The new investment decision enables households to either buy whole-sale electricity from the grid or invest in rooftop PV. This decision is modelled with a multi-nomial logit (see Eq. (6)) and compares the prices of whole-sale electricity and a rooftop PV system. Eq. (6) assigns the largest share to the lowest cost option, but also assigns some share to a higher cost option. The market share (MS) (%) for option a compared to option b, per household i, per income quintile j, and per region r (van Vuuren, 2007) equals:

$$MS^{a}_{i,j,r} = \frac{\exp - \lambda\left(E\_LCOE_{i,j,r}\right)_{a}}{\sum_{b} exp - \lambda(RT\_LCOE_{i,j,r})_{b})} \tag{6}$$

where E_LCOE is the levelized cost of electricity (LCOE) from the electricity module (\$ kWh^{-1}), RT_LCOE is the LCOE of rooftop PV (\$ kWh^{-1}), and λ is the so-called logit parameter that reflects the behavioural sensitivity to prices. This parameter was calibrated to historically observed sensitivity to prices. The rooftop electricity costs were calculated following Eq. (3), with an exception that the annuity factor (ann) is now calculated for the individual income groups with the CDR from Eq. (5). An important assumption, as indicated in Eq. (3), is that we assume that rooftop PV is comprised of similar technological components as utility-scale PV. Yet, we also assume that there are additional costs incurred with rooftop installation. This means that the technology development based on the learning curve (see Eq. (4)) is influenced by the capacity of both utility-scale PV and rooftop PV.

The total rooftop PV capacity (sum of all urban/rural/income groups) is added to the general power pool of the electricity module. This ensures that rooftop PV contributes to the technological learning equations, but also ensures that the electricity system includes rooftop PV in operational issues that relate to intermittency and grid stability (see Appendix, Text A1, for more detail on the electricity module). Finally, a self-consumption rate of 30% is assumed, to model that households, on average, consume some of the electricity directly inside the household, without supplying it to the grid (Lang et al., 2015). This factor is kept constant over time.

2.3. Scenarios

In order to assess the role of rooftop PV in future energy systems, we use the IMAGE implementation of the SSP2 scenario [12,31]. The SSP2 scenario describes a world in which social, economic, and technological

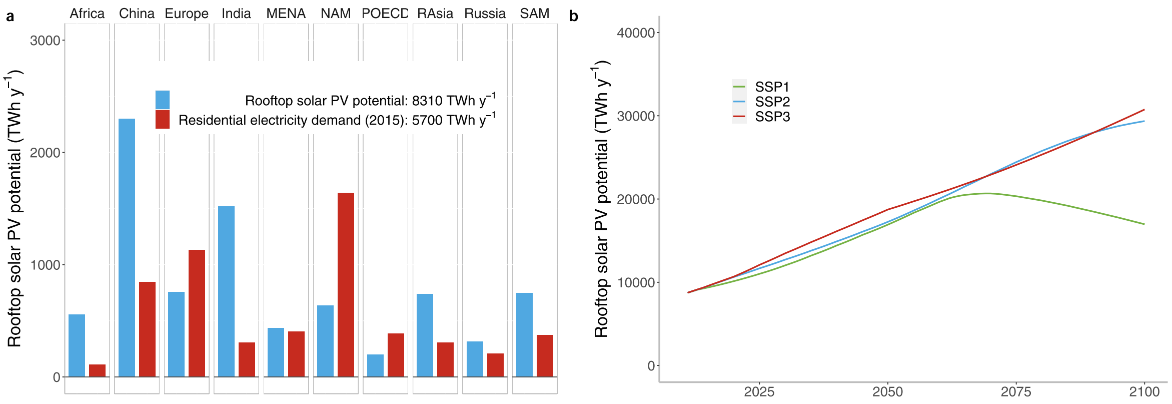

Fig. 3. Technical rooftop PV potential and its development in different SSP scenarios. **a**, The technical rooftop PV potential and the IMAGE 2015 residential electricity demand (IMAGE results are calibrated to [20]) (MENA = Middle East and North Africa, NAM = North America, POECD = Pacific OECD, RAsia = Rest of Asia (Asia excluding India and China), SAM = South-America). **b**, The development of the technical potential of rooftop PV for SSP1, SSP2, and SSP3 scenario (see Appendix, Text A2 and Figs. A4, A5 for more details on the SSP scenarios).

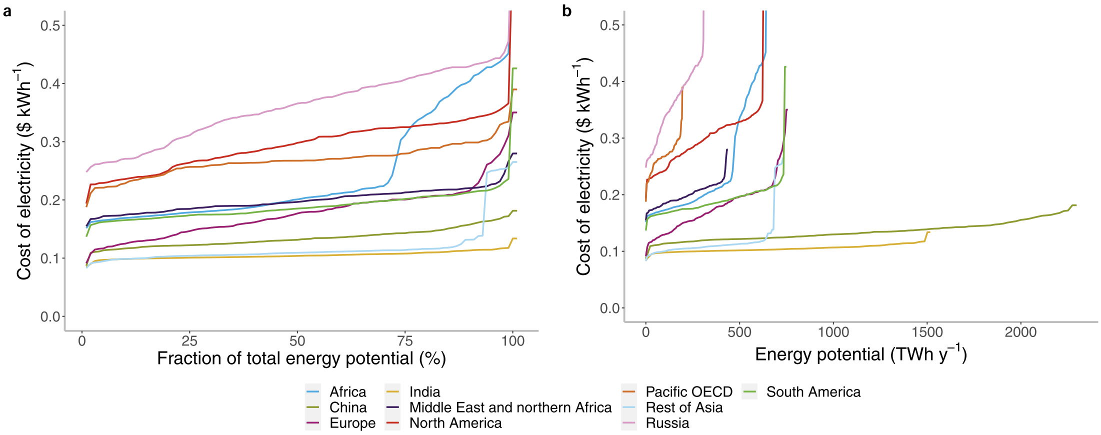

Fig. 4. Regional cost-supply curves for rooftop PV. a, Relative to technical potential and b, Absolute cost-supply curves.

trends follow a median trajectory. The economic development in this scenario is modest and population growth follows a median scenario more-or-less levelling off in the second half of the century (for more information see Appendix, Text A2 and Figs. A4, A5). The regional electricity demand per sector for the IMAGE-SSP2 baseline scenario is shown in Fig. 2. In this scenario global electricity demand doubles by 2050, but regions like India, however, are expected to grow fivefold. Most of this growth comes from the residential sector, the services sector, and industry sector, but some growth is also expected from the transport sector. Compared to the industry sector, the building sector grows faster because of a higher electrification rate, a growth in the services sector, and a growth of household floor space.

We defined five scenarios to explore the impact of the rooftop PV in future energy systems (Table 2). These scenarios combine climate policy with specific policy factors for rooftop PV. At first, a baseline scenario with (SSP2_RT) and without (SSP2) rooftop PV. Then, an additional baseline scenario that includes a net-metering policy (SSP2_RTPol). Subsequently, a climate-policy scenario with (SSP2_RTPol_ClimPol) and without (SSP2_ClimPol) rooftop PV-including net-metering for the scenario with rooftop PV. To emphasize levels of uncertainty, we show the results for other SSPs at several occasions (see Appendix, Text A2 and Figs. A4, A5 for more details on the SSP scenarios).

3. Results

3.1. Technical and economic potential of rooftop PV

We estimated a global roof area of 113 billion m^2, with 36 billion m^2 being potentially suitable for rooftop PV which equals 4.7 m^2 capita^{-1}. Estimates of available roof area in the Netherlands show 7.3 m^2 capita^{-1} (using the suitability factor in this study), which is similar to our western European estimate (7.4 m^2 capita^{-1}) [32]. Combined with irradiance data and conversion efficiencies this leads to a global annual potential of rooftop PV 8.3 PWh y^{-1}. This is roughly 1.5 times the global residential electricity demand in 2015 (Fig. 3a). The global average production per square meter is 230 kWh m^{-2} y^{-1}. This is roughly compatible with empirical findings in The Netherlands, showing an average production of the current installed capacity of 140 kWh m^{-2} y^{-1} (if we look at Dutch grid cells, we find 141–167 kWh m^{-2} y^{-1}) [33]. The potential for rooftop PV is particularly high in China, India, western Europe, and the US, which can be explained by the large available roof area. In China and India, the roof area is driven by a large population, but in western Europe and the US roof area is driven by larger household floor spaces. Over time, the potential grows as a function of an increase in floor space, which is driven by population, GDP, and household size (Fig. 3b). The global rooftop PV potential doubles by 2050 in all SSP scenarios (see Appendix, Text A2 and Figs. A4, A5 for more details on the SSP scenarios, including SSP1 and SSP3).

In Table 3 we present our results on roof area and technical potential estimates in comparison with data presented earlier. Starting with the

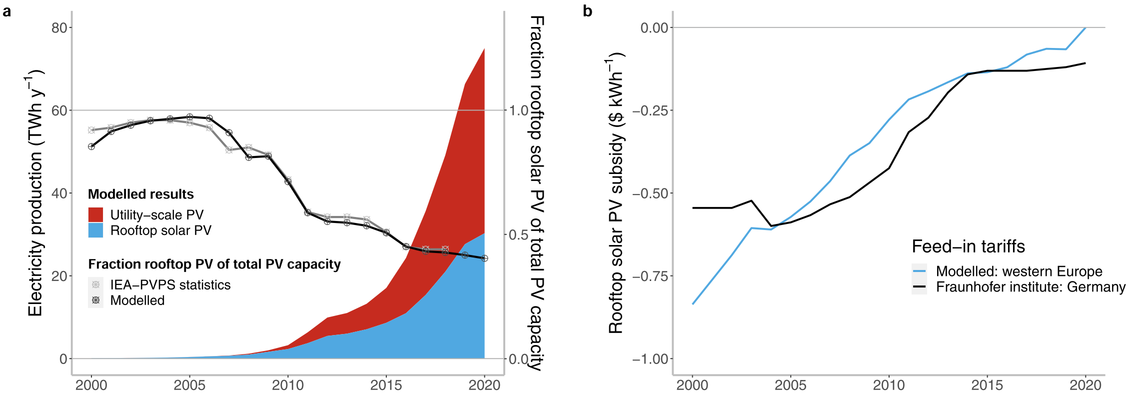

Fig. 5. Historical development of utility-scale PV and rooftop PV, and its subsidies. **a**, The modelled historical development of utility-scale PV and rooftop PV in PWh y^{-1}, compared to statistical data from IEA-PVPS reports between 2000 and 2019 [3]. **b**, The calculated subsidies for the western Europe and the German subsidy [40].

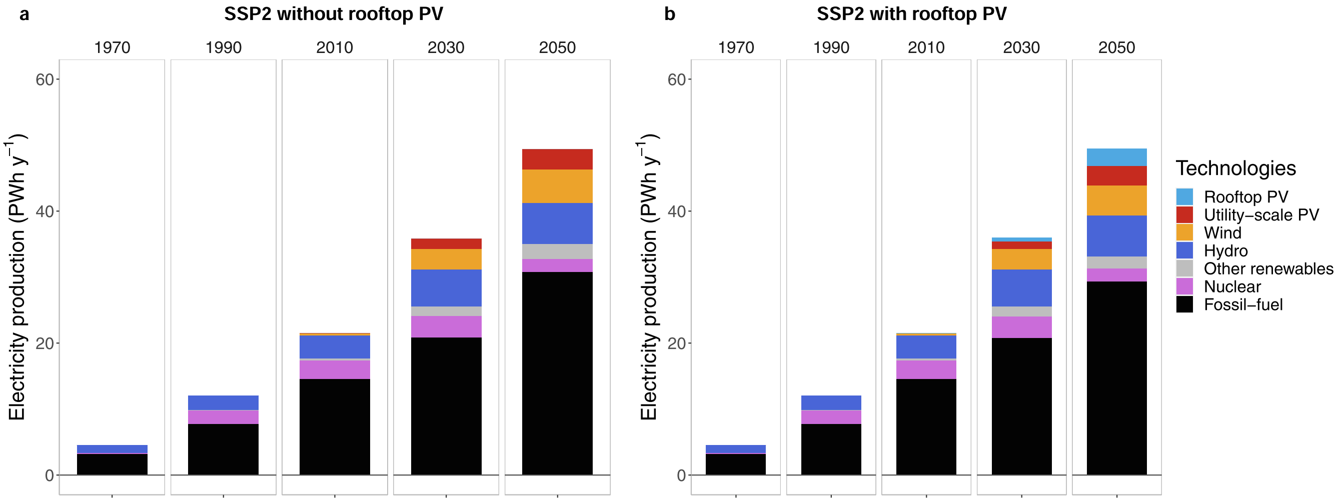

Fig. 6. The electricity production development from 1970 to 2050. **a**, SSP2 without rooftop PV. **b**, SSP2 with rooftop PV.

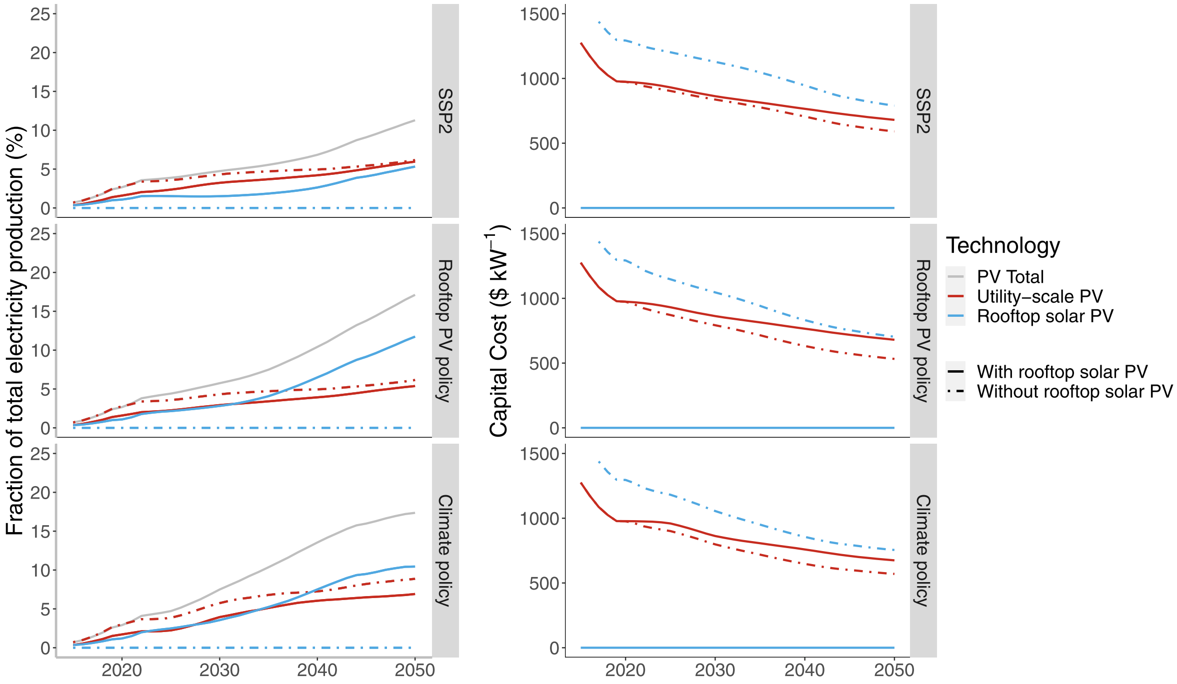

Fig. 7. The fraction of global electricity production supplied by both PV systems (left) and the development of capital cost of both systems (right) in different scenarios. The variations of utility-scale PV capital costs after 2030 occur due to system integration costs such as required backup costs. For regional cost see Appendix, Table A4.

area, Hoogwijk [34] estimated a global suitable roof surface area of 15,000 km^2 based on an aggregated analysis relating GDP per capita directly to roof surface area. Our estimates are about a third of that value (36,237 km^2), but is similar to results from Deng [35] who used a methodology similar to ours. Our estimates for the US (2,637 km^2) are lower than those of Gagnon [18] (4950 km^2), because we do not include service sector buildings. Our EU roof surface estimates (4,015 km^2) are in the same range as the ones from Defaix [36] (3,678 km^2). The highly detailed regional studies for Switzerland and Spain show some similarity but also differences [37,38]. Comparing the potential, Deng [35] estimates are close to this study, as are the estimates for the US and the EU.

Using Eq. (3) and the capital costs from Table 1, we calculated the LCOE of rooftop PV per grid cell ($ kWh^{-1} cell^{-1}). Combining this LCOE map with the rooftop PV technical potential map (kWh cell^{-1}), cost-supply curves were generated by sorting (from low to high) the cells in the LCOE map while simultaneously adding the same cells from the technical potential map. Fig. 4 shows the regional cost-supply curves for ten major world regions in relative (Fig. 4a) and in absolute form (Fig. 4b). Distinct patterns are seen across regions. First, every region starts at a different cost level because each region has different investment costs (Table 1). Second, the shape of the curves differs per region. The region named 'rest of Asia' (that is Asia excluding China and India), for example, shows a distinctly flat shape with a large fraction of its potential at low costs. In contrast, Europe shows a steeper shape with costs increasing as more potential is used. Note that, over time, the regional specific capital costs decline with technological learning and converge in the scenarios.

3.2. Model calibration for historical period

After introducing the cost-supply curves to the IMAGE model we calibrated the model to statistical data. This calibration was done by adding subsidy to the price of rooftop PV that is necessary to achieve the amount of capacity as reported by IEA-PVPS [3], from which the fraction of rooftop PV also was extracted. The subsidies are calculated in two steps. The first step forces the model to install the historical amount of PV capacity (utility-scale + rooftop PV). In a second step, the reversed multi-nomial logit function (Eq. (6)) is used to calculate the required subsidy. In Fig. 5a the modelled results are presented and compared to the IEA-PVPS 2000–2019 statistical data [3]. The results in Fig. 5a were generated by using subsidies shown in Fig. 5b, which is compared to the historical feed-in tariffs from Germany.

Although comparable, the calculated subsidy is lower than the subsidy from Germany, also called a feed-in tariff [40]. This has several reasons. First, the calculated subsidy is for the whole of western Europe and includes high-irradiance areas such as Spain. Secondly, the average whole-sale electricity price for western Europe is lower than for Germany. Thirdly, this is a result of the multi-nominal logit function. A logit formulation, by definition, allows some market share to be assigned to a more expensive option, thereby, incorporating some of the subsidy (see explanation below Eq. (6)). Finally, in reality other policy incentives have been used, such as tax credits or rebate programs that do not show up in the reported subsidy [6].

3.3. Scenario

3.3.1. Results at global scale

In the baseline scenario (SSP2), combined PV (utility-scale PV and rooftop PV) as a share of the total electricity production increased in 2050 by 80% (from 6% to 11%) when rooftop PV was included (SSP2_RT) (Figs. 6 and 7). The combined PV capacity in 2050 was projected to be 3500 GW: 1700 GW more than in the scenario that excluded rooftop PV. This is a result of the combined learning of utility-scale and rooftop PV, showing the importance of rooftop PV for understanding overall PV dynamics. In terms of cost, this added capacity drives learning effects that decreased PV capital costs by 4–8% between 2020 and 2030. Although there is a net increase in the use of renewables, rooftop PV takes some market share from other renewables. In comparison to a baseline scenario without rooftop PV (SSP2), utility-scale PV's electricity production decreased by 90 TWh y^{-1} (−3%) and wind decreased by 600 TWh y^{-1} (−11%). Of the fossil-fuel technologies, coal decreased by 981 TWh y^{-1} (−5%), and the use of gas by 619 TWh y^{-1} (9%).

The role of rooftop PV depends on policy assumptions, as shown in Fig. 7. The rooftop PV policy scenario (SSP2_RTPol), shows that net-metering can increase the combined PV share by 180% compared to SSP2_RT, lifting the combined PV share from 6% to 17% of the total electricity production. In the climate policy scenario (SSP2_ClimPol) the combined PV share in 2050 increased by 125% when rooftop PV was included (SSP2_RTPol_ClimPol) (from 8% to 18% of the total electricity production). The calculated combined PV capacity in 2050 is 6000 GW: 4000 GW more than in the scenario that excludes rooftop PV. In terms of cost, this results in a 4–10% cost decreased between 2020 and 2030. As occurred in the baseline scenario, rooftop PV caused a net increase of the use of renewables but took away market shares from other technologies. While in the baseline scenario the use of coal and gas were reduced; the inclusion of rooftop PV in the climate policy scenario (SSP2_RTPol_ClimPol) affects mostly other renewables: utility-scale PV (−21%), onshore wind (−7%), offshore wind (−10%), nuclear (−10%) and carbon capture and storage (CCS) from coal (−18%) and gas (−18%). The

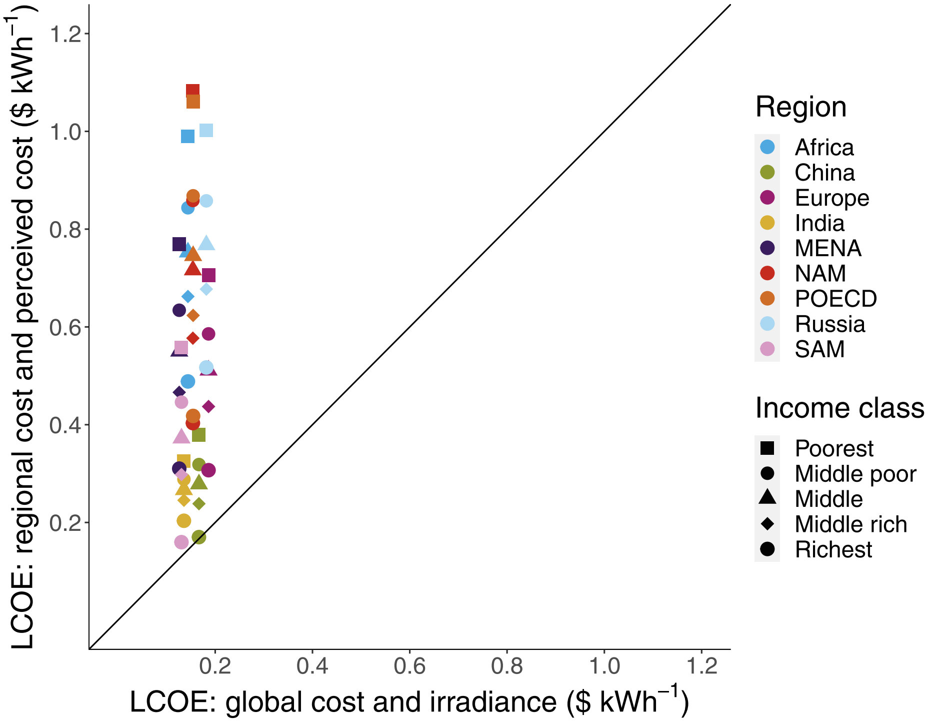

Fig. 8. The rooftop PV LCOE based on just irradiance (x-axis) versus the LCOE based on perceived costs, regional capital cost, and irradiance (y-axis).

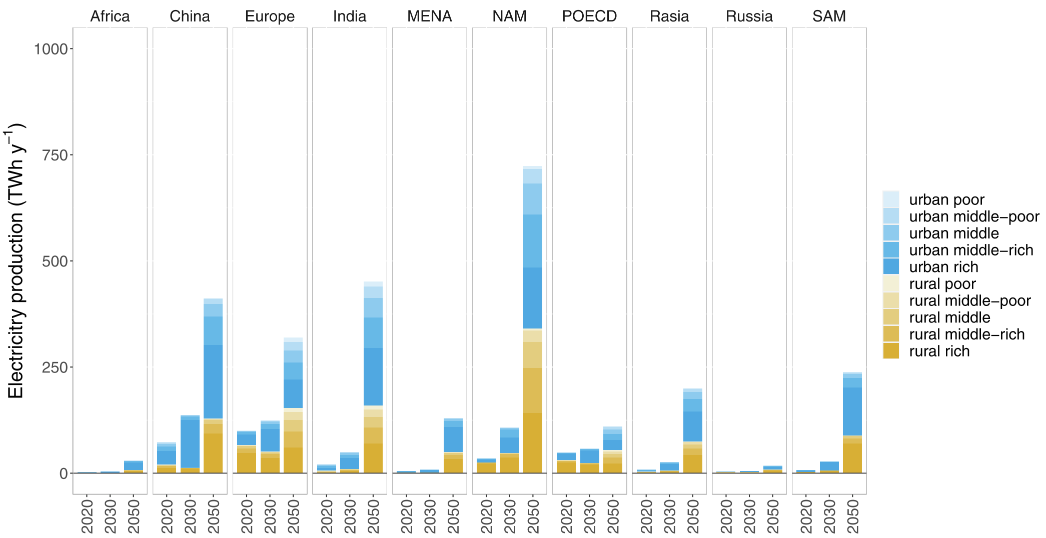

Fig. 9. Regional production of rooftop PV (PWh y^{-1}) in the baseline scenario with rooftop PV (SSP2_RT) in the year 2020, 2030 and 2050. (MENA = Middle East and north Africa, NAM = North America, POECD = Pacific OECD, RAsia = Rest of Asia (Asia excluding India and China), SAM = South America).

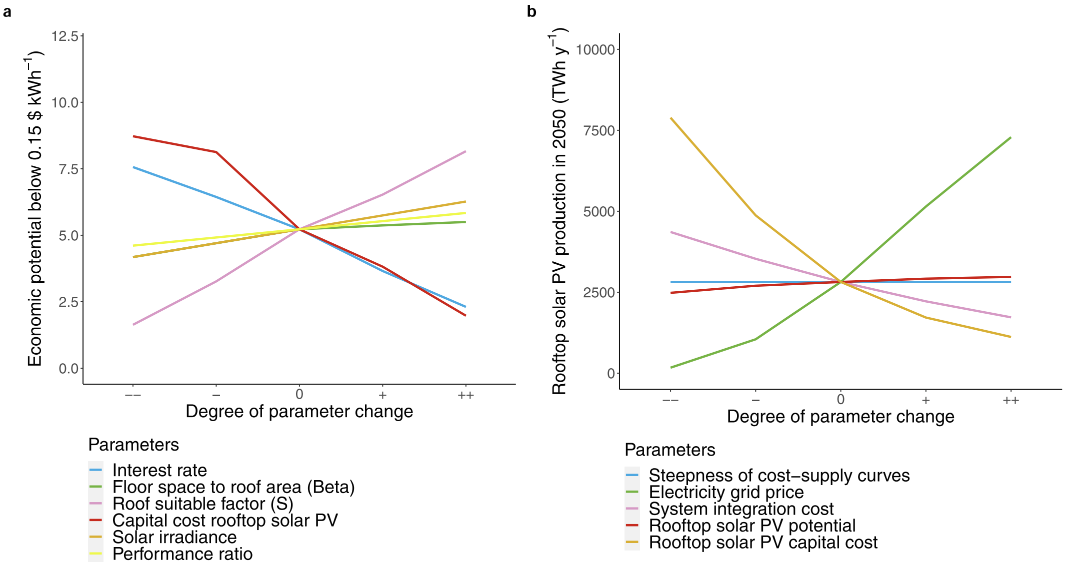

Fig. 10. Sensitivity analyses. **a**, Sensitivity runs on the economic potential (<0.15 $ kWh^{-1}). See Appendix Table A5 for the defined degree of parameter change. **b**, Sensitivity runs with the IMAGE model on the rooftop PV production in 2030 (TWh y^{-1}). See Appendix Table A6 for defined degree of parameter change.

use of bio-energy combined cycle increased with 30%, however, to compensate for the loss of stability in the electricity system. In technical terms: to adjust for the loss of available residual full load hours and system reserve requirements. Market penetration is further explored in the sensitivity analyses in the discussion section (see Fig. 10).

3.3.2. Results at regional scale

There are various factors that influence regional differences in the deployment of rooftop PV.

a) Irradiance. Some regions have higher irradiance levels leading to a higher potential and lower costs (see Fig. 4).
b) Regional capital costs for rooftop PV vary significantly, from 1460 $ kW^{-1} in India to 3480 $ kW^{-1} in the US (Table 1). Although these capital costs will likely converge in the future through learning and trade, they have a distinct effect on the short-term deployment of rooftop PV.
c) Upfront investment is required to install rooftop PV systems. These investments are perceived differently for different income groups: a high-income household perceives it at lower costs than a low-income household. This is expressed by the consumer discount rates (see Section 2.2.3).
d) Taxes and subsidies, that differ per technology and per region.
e) Costs of competing technologies, that also differ per region.

Regional differences in rooftop PV

We can compare the impact of the physical factors (a) to the other factors (b-d) that determine rooftop PV costs, by calculating the costs based on irradiance only to the final perceived prices by the households per region based on the consumer discount rates and the regional capital cost, as used in the IMAGE model (Fig. 8[1]). What Fig. 8 clearly shows is that the spread caused by irradiance alone (horizontal) is smaller than the spread caused by the regional capital cost and the perceived costs (vertical). Solar irradiance causes approximately 10% of the cost variance; the other two factors 90%.

Prices of alternative options.

Electricity prices are the benchmark rooftop PV prices are compared to. The electricity price is the average price of the whole electricity market, with added taxes, T&D costs, and subsidies. In the IMAGE model this price is based on the dynamics of 28 different combinations of renewable, nuclear, fossil-fuel, and bio-energy options. The regional prices differ between 0.10 and 0.20 \$ kWh^{-1} which is consistent with prices reported in literature [30]. Comparing western Europe with the Middle East, for example, illustrates how the benchmark effect works. In western Europe, rooftop PV (0.24 \$ kWh^{-1}) is approximately 0.04 \$ kWh^{-1} more expensive than the whole-sale electricity price (around 0.20 \$ kWh^{-1}). In the Middle East, however, it is 0.06 \$ kWh^{-1} more expensive, despite a lower rooftop PV price of around 0.16 \$ kWh^{-1}. Here cheap fossil-fuels, low taxes, and high subsidies result in a whole-sale electricity price that is half of the European price. The result is thus a lower deployment of rooftop PV in the Middle East compared to western Europe (see Fig. 9).

Deployment per region

The three regional factors (capital cost, perceived cost, and electricity prices) drive the deployment of rooftop PV (Fig. 9). The regions with the highest deployment of rooftop PV in 2050 are North America (27% of global rooftop PV capacity, most from the US), India (with 17%), and Europe (with 12%). The results from the US are similar to the results found by Drury [41], whom presents a lower estimate of 30GW in 2030 without incentives and a higher estimate of 270GW with incentives. Our results for the US in 2030 range from 65 GW (without incentives) to 220GW (with net-metering incentives). The reason the US shows higher deployment than China, for example, even though China has a higher technical potential (see Fig. 3), is because the US have a larger share of the population in high-income groups in combination with higher whole-sale electricity prices. The reason Europe deploys less rooftop PV than the US, despite similar technical potential and electricity prices, is because a larger share of the US cost-supply curve is in the cost competitive range.

The technical potential (i.e. the available roof area) can become a limiting factor in some regions. In several regions, the deployment in the model by 2050 is more than half the technical potential. North America, for instance, uses 60%. Globally, in the SSP2 baseline, 25% of the 2015 rooftop PV technical potential is utilized by 2050. Interestingly, some regions exceed their 2015 rooftop PV potential. In 2015, India has a potential of about 1500 TWh y^{-1} but, by 2100, produces almost 5000 TWh y^{-1}; more than 300% of its 2015 potential. This is an effect of the growth in roof area driven by population and GDP growth. This effect is seen in most developing regions, including Africa, Asia, and South America.

4. Discussion

This study estimates global technical and economic rooftop PV potential and performs a long-term scenario assessment with a broad range of regional factors, going beyond earlier scenario analysis that focused mainly on utility-scale PV. The results show that current global rooftop potential is 1.5 times the residential electricity demand. The market penetration of rooftop solar PV is much more dependent on socio-economic and policy factors than on the biophysical potential. Several aspects require further discussion.

The first aspect concerns the lack of data in the roof area estimates. Census data on buildings, for example, were found for a selected number of countries only; mainly developed countries. The same holds true for regional differentiation of the rooftop suitability factor (0.32, S in Eq. (2)), and historical data to develop dynamic floor-space-to-roof-area coefficients (β in Eq. (2)). As regions develop and construction skills improve, houses are built higher, and coefficients will likely become lower. Especially for developing regions, this needs to be included to avoid an overestimation of the technical potential. A second point of discussion is that this study considers residential buildings but neglects buildings from the service sector. The data and parameters we used to calculate floor space to roof area could not be found for the services sector. Including roofs from the services sector, however, might increase the potential significantly, as also shown by studies that did include the service sector roof area Gagnon [18,36]. The third point of discussion concerns the use of an IAM to study rooftop PV. IAMs are designed to assess long-term trends and are, therefore, less well equipped for short-term effects in specific regions.

To assess the sensitivity of key parameters we performed two analyses. In the first, assumptions regarding the economic potential were tested (Fig. 10a), and, in the second analysis, model and scenario assumptions were tested (Fig. 10b). Four parameters cause the economic potential to increase when parameters increase: the floor-space-to-roof-area coefficients (β in Eq. (2)), the roof area suitable factor (S in Eq. (2)), the performance ratio (PR in Eq. (1)), and the solar irradiance. The interest rate and capital costs have an opposite effect. In the scenario sensitivity, the effects on the rooftop PV production in 2050 caused by the cost-supple curve and the maximum potential were not influential, although this might be different later in the century when developing regions dominate the PV deployment. The three factors that are influential in 2050 are: the system integration cost, the PV capital cost, and the whole-sale electricity price. The first component, refers to the costs necessary to integrated intermittent supply from solar PV in the electricity system, such as battery storage or back-up capacity. This cost component becomes, by 2050, influential for the adoption of rooftop PV; halving these cost could add almost 50% of rooftop PV production. Results from a separate analyses done for the year 2030, show a much lower sensitivity, indicating that it's influence grows over time as higher shares of intermittent supply penetrate the system. The latter two factors (PV capital cost and whole-sale electricity price) are part of the new household decision and show non-linear behaviour, caused by the multi-nominal logit equation (Eq. (6)). Halving the PV capital cost could lead to a three-fold increase of the rooftop PV production in 2050 but, interestingly, so can a doubling of the electricity price.

5. Conclusion and policy implications

This study estimates global technical and economic rooftop photovoltaic potential and performs a long-term scenario assessment with a broad range of regional factors. Physical information on solar irradiation and roof area was combined with cost data to derive regional cost-supply curves that were inserted into the IMAGE Integrated Assessment Model.

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[1] For the purpose of this analyses a global capital cost of 1600 \$ kW^{-1} is assumed [6] IRENA. IRENA Cost and Competitiveness Indicators: Rooftop Solar PV. Abu Dhabi: International Renewable Energy Agency; 2017. For regional capital cost see Table 1 and for perceived costs Eq. (5) on CDRs.

The possibility per household to decide for rooftop photovoltaic was modelled in IMAGE through a new investment decision that compares the whole-sale electricity price with the price of rooftop photovoltaic. This decision was implemented with region specific characteristics, including factors such as income levels, retail electricity prices, taxes, and investment costs. Based on our analysis, we draw the following conclusions.

The rooftop photovoltaic cost-supply curves show a potential of 8.3 PWh y^{-1} in 2015 on a global suitable roof area of 36 billion m^2 and cost levels of 0.09–0.5 $ kWh^{-1}. The total potential of 8.3 PWh y^{-1} is roughly 1.5 times the 2015 global residential electricity demand. The potential and costs estimated in this study are consistent with those reported by literature.

Rooftop photovoltaic key driver in photovoltaic market; historical behaviour well simulated. In IMAGE, the cost-supply curves were linked with the residential module and the electricity module to represent household investment behaviour on rooftop photovoltaic. Using internal model simulations, historical feed-in tariff subsidies and historical capacity data were mimicked closely.

Rooftop photovoltaic has been important in the past and will likely remain so in the future. We used the IMAGE model to compare two scenarios-one in which we simulated the availability of rooftop photovoltaic and one in which we did not. We found that the share of photovoltaic in the total electricity production increases by 80% in 2050 in the scenario that includes rooftop photovoltaic. Deployment is highest in Europe and the US, regions with large roof areas and a large share of the population with high income. Despite lower roof area per capita, China and India can also see high deployment due to large population and rising income levels. In the analysis, rooftop photovoltaic drives down the costs of overall photovoltaic through learning, decreasing photovoltaic capital costs further by 4–10% between 2020 and 2030. In a climate policy scenario with rooftop photovoltaic, total photovoltaic production increased 150% compared to the scenario without rooftop photovoltaic.

Low-irradiation western Europe better than high-irradiation Middle East. Socio-economic and policy factors are more important for near-term deployment of rooftop photovoltaic than physical factors. The deployment of rooftop photovoltaic depends on the perceived costs for consumers versus other available options. Differences in income levels, whole-sale electricity prices, and investment costs dominate regional deployment.

The analyses in this paper shows that the deployment of rooftop PV is regionally depended. Some of the regional differences, however, can be elevated through global market measures. PV panel prices, for example, differ per region, which global trade without barriers could reduce. Trade, and other forms of economic collaboration, could also alleviate poverty levels lifting more people into high-income levels with which they could afford to invest in rooftop PV systems. Regional policy measures, such as subsidies, must be carefully fitted to the regional context, and must take into account existing energy prices, tax levels, and in particular income levels and perceived cost (as opposed to real cost) to be effective. This regional context is, however, not static and changes continuously. Policy measures to incentivise rooftop PV are, therefore, well advised to be adaptable over time.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

David E.H.J. Gernaat: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Harmen-Sytze Boer:** Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Louise C. Dammeier:** Data curation, Formal analysis, Investigation, Methodology, Software, Writing - original draft. **Detlef P. Vuuren:** Conceptualization, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing.

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.

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Appendix A

Text A1: Description of the electricity module

The electricity module described by de Boer [26] simulates generation of electricity by various technologies. These technologies compete for a share in investments based on technology costs per amount of generated electricity. These technology costs, in turn, change over time, as it is subject to technology development and depletion effects. TIMER’s electricity module describes 28 different combinations of renewable, nuclear, fossil fuel and bio-energy electricity technologies. For each fuel (coal, oil, natural gas, bio-fuel), the model distinguishes a conventional technology, gasification and/or combined cycle technology, combined-heat-and-power (CHP) technology, carbon capture and storage (CCS) technology and CHP combined with CCS technology.

LCOEs are determined per load band, each load band having a different load factor based on the shape of the (residual) load duration curve. The LCOE contains integration costs like backup costs, storage costs and the costs of curtailments. In that way, investments account for expected electricity that will be produced by a technology [26]. After the investment decisions, a power system operation algorithm describes the use of the technologies for power generation. This is done based on a merit order strategy, based on low operational costs and the characteristics of the different technologies in various load bands as described by de Boer [26].

Text A2: Description of the Shared Socio-economic Pathways (SSPs)

The SSP framework defines five storylines that differ in the degree of challenge for mitigation and in the degree of challenge for adaptation [42]. Three storylines are used for analyses [12]. The SSP1 scenario depicts a world that aims for green growth and sustainable development. Climate policy is not implemented directly, but through technological developments for a higher energy efficiency and a better use of

Table A1
Census data on floors.

# floors per household/Country	1	2	3	4	5	6	7	8	9	10
Qatar[1]	38.6%	41.6%	7.7%	2.5%	3.1%	2.1%	1.5%	1.2%	0.9%	0.8%
US[2]	19.4%	20.0%	38.0%	4.8%	4.8%	4.8%	8.3%	0.0%	0.0%	0.0%
Hungary[3]	95.7%	4.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Australia[4]	78.4%	2.8%	8.8%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Albania[5]	74.4%	8.8%	5.6%	3.1%	2.0%	2.2%	1.5%	1.1%	0.9%	0.6%
Japan[6]	6.4%	21.3%	12.4%	13.7%	3.4%	4.1%	4.8%	5.5%	6.2%	22.3%
Jordan[7]	39.6%	21.6%	21.2%	10.7%	5.0%	1.3%	0.4%	0.1%	0.0%	0.0%
Finland[8]	60.0%	25.1%	7.6%	3.0%	1.7%	1.0%	0.7%	0.5%	0.3%	0.2%
Greece[9]	35.6%	25.4%	17.9%	8.0%	5.4%	4.7%	3.1%	0.0%	0.0%	0.0%
Switzerland[10]	2.4%	14.6%	37.3%	20.7%	11.0%	6.1%	3.8%	2.0%	1.0%	1.2%
Czech Republic[11]	31.7%	31.7%	9.6%	12.8%	14.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Bahrain[12]	38.3%	42.1%	12.1%	3.0%	1.0%	0.4%	3.1%	0.0%	0.0%	0.0%
Cape Verde	31.7%	31.7%	9.6%	12,8%	14.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Turkey[13]	6.1%	5.9%	10.8%	14.3%	20.8%	42.1%	0.0%	0.0%	0.0%	0.0%
Mauritius[14]	52.4%	38.4%	7.2%	1.3%	0.2%	0.1%	0.5%	0.0%	0.0%	0.0%
Germany 1971[15]	15.3%	37.3%	21.0%	16.2%	6.9%	0.4%	0.2%	0.1%	0.0%	1.2%
Germany 1981[16]	15.6%	32.7%	17.6%	15.0%	12.7%	2.2%	1.5%	1.0%	0.5%	1.2%
Indonesia 1990[17]	94.8%	5.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Indonesia 1995[18]	94.5%	5.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Kyrgyz Republic[19]	77.2%	3.5%	10.0%	5.0%	1.4%	1.2%	0.8%	0.5%	0.4%	0.3%
Spain 1991[20]	14.7%	21.0%	7.7%	9.7%	12.7%	9.0%	5.9%	5.9%	4.3%	9.2%
Spain 2011[21]	14.7%	34.4%	13.3%	10.9%	11.4%	7.6%	4.9%	4.9%	2.5%	5.7%

The percentage of household with 1–10 floors per country.

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Table A2
Floor space to roof area Beta.

IMAGE Region	Countries with statistical data	Year of statistical data	Floor space[1]	Households	Beta	Roof area
Middle East	Qatar	2010	19.6	51,110,390	0.64	12.54
US	US	2009	53.24	89,840,570	0.46	24.49
Central Europe	Hungary	2011	32.82	43,699,870	0.98	32.16
Oceania	Australia	2001	47.71	9,854,651	0.85	40.56
Central Europe	Albania	2011	32.82	43,699,870	0.83	27.24
Japan	Japan	2014	33.14	49,569,600	0.3	9.94
Middle East	Jordan	2005	17.8	41,755,040	0.61	10.86
Western Europe	Finland	2014	43.74	1.74E+08	0.77	33.68
Western Europe	Greece	2010	43.21	1.67E+08	0.59	25.5
Western Europe	Switzerland	2013	43.63	1.72E+08	0.31	13.53
Central Europe	Czech Republic	2011	32.82	43,699,870	0.57	18.71
Middle East	Bahrain	2001	17.29	35,710,320	0.65	11.24
Western Africa	Cape Verde	2010	9.96	67,852,710	0.68	6.77
Turkey	Turkey	2011	31.03	19,620,374	0.27	8.38
Eastern Africa	Mauritius	2010	6.66	52,581,010	0.74	4.93
Western Europe	Germany	1971	31.09	87,486,580	0.47	14.61
Western Europe	Germany	1981	35.18	1.3E+08	0.45	15.83
Indonesia	Indonesia	1990	10.63	35,576,540	0.97	10.31
Indonesia	Indonesia	1995	11.23	43,714,370	0.97	10.89
Central Asia	Kyrgyz Republic	2009	17.4	20,857,767	0.84	14.62
Western Europe	Spain	1991	39.13	1.59E+08	0.37	14.48
Western Europe	Spain	2011	43.4	1.69E+08	0.45	19.53
World	World	Weighted Average	34.91	1.71E+09	0.56	19.55

[1] IMAGE household data calculated with Eq. (2).

Table A3
Floor space to roof area coefficient (β in Eq. (2)) allocated to IMAGE regions.

IMAGE Regions	Available data	Allocated region	Beta
Canada	–	US	0.46
US	US	US	0.46
Mexico	–	Average[1]	0.56
Rest Central- America	–	Average[1]	0.56
Brazil	–	Average[1]	0.56
Rest South- America	–	Average[1]	0.56
Northern-Africa	–	Middle-East[1]	0.63
Western-Africa	Western-Africa	Western-Africa	0.68
Eastern-Africa	Eastern-Africa	Eastern-Africa	0.74
Southern-Africa	–	Average[1]	0.56
Western-Europe	Western-Europe	Western-Europe[1]	0.50
Central-Europe	Central-Europe	Central-Europe[1]	0.79
Turkey	Turkey	Turkey	0.27
Ukraine +	–	Central-Europe[1]	0.79
Asia-Stan	Central-Asia	Central-Asia	0.84
Russia +	–	Central-Asia	0.84
Middle-East	Middle-East	Middle-East[1]	0.63
India +	–	Indonesia	0.97
Korea	–	Japan	0.30
China +	–	Average[1]	0.56
Southeastern Asia	–	Indonesia	0.97
Indonesia +	Indonesia	Indonesia	0.97
Japan	Japan	Japan	0.30
Oceania	Oceania	Oceania	0.85
Rest S.Asia	–	Indonesia	0.97
Rest S.Africa	–	Average[1]	0.56
Average		**Average**[1]	0.56

[1] Household weighted average of the available countries.

Table A4
Overview of technical and economic assumptions of utility-scale PV and rooftop PV in SSP2. Cost data in 2015 is based on IEA [64] and cost data in 2019 is based on IEA [20].

			Lifetime (years)		OPEX ($\$$ kW^{-1} (2015))		CAPEX ($\$$ kW^{-1} (2015))				
Region	Technology	Learning rate	Technical	Economic	O&M fixed	O&M variable	2015	2020	2030	2040	2050
Western Europe	Utility-scale PV	0.2	25	20	17	0	1320	974	837	706	591
	Rooftop PV	0.2	25	20	20	0	1600	1293	1128	946	790
Central Europe	Utility-scale PV	0.2	25	20	17	0	1320	975	838	707	592
	Rooftop PV	0.2	25	20	20	0	1600	1294	1130	947	791
US	Utility-scale PV	0.2	25	20	17	0	2220	1315	950	701	588
	Rooftop PV	0.2	25	20	20	0	3480	2867	1689	940	786
Canada	Utility-scale PV	0.2	25	20	17	0	2220	1317	956	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2870	1698	947	791
Oceania	Utility-scale PV	0.2	25	20	17	0	2220	1316	955	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2869	1697	947	791
Japan	Utility-scale PV	0.2	25	20	17	0	2020	1420	991	707	592
	Rooftop PV	0.2	25	20	20	0	2880	1930	1352	947	791
Korea	Utility-scale PV	0.2	25	20	17	0	2020	1421	992	707	592
	Rooftop PV	0.2	25	20	20	0	2880	1931	1353	947	791
Russia	Utility-scale PV	0.2	25	20	17	0	2580	1640	1067	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2195	1444	947	791
Turkey	Utility-scale PV	0.2	25	20	17	0	2580	1640	1067	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2194	1444	947	791
Ukraine	Utility-scale PV	0.2	25	20	17	0	2580	1640	1067	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2194	1444	947	791
Central Asia	Utility-scale PV	0.2	25	20	17	0	2580	1640	1067	707	592
	Rooftop PV	0.2	25	20	20	0	3480	2195	1444	948	791
China+	Utility-scale PV	0.2	25	20	17	0	1360	790	684	582	492
	Rooftop PV	0.2	25	20	20	0	1480	1005	883	752	638
Southeast Asia	Utility-scale PV	0.2	25	20	17	0	1360	792	686	583	493
	Rooftop PV	0.2	25	20	20	0	1480	1008	885	753	640
Indonesia	Utility-scale PV	0.2	25	20	17	0	1360	793	686	583	494
	Rooftop PV	0.2	25	20	20	0	1480	1008	885	753	640
Rest of South Asia	Utility-scale PV	0.2	25	20	17	0	1360	793	686	584	494
	Rooftop PV	0.2	25	20	20	0	1480	1008	886	754	640
India	Utility-scale PV	0.2	25	20	17	0	1340	706	613	524	447
	Rooftop PV	0.2	25	20	20	0	1460	801	706	612	531
Middle East	Utility-scale PV	0.2	25	20	17	0	2360	1961	1178	707	591
	Rooftop PV	0.2	25	20	20	0	3000	2545	1566	947	791
North Africa	Utility-scale PV	0.2	25	20	17	0	2400	1625	1062	707	592
	Rooftop PV	0.2	25	20	20	0	2840	1974	1364	947	791
West Africa	Utility-scale PV	0.2	25	20	17	0	2400	1626	1062	707	592
	Rooftop PV	0.2	25	20	20	0	2840	1974	1364	947	791
East Africa	Utility-scale PV	0.2	25	20	17	0	2400	1626	1062	707	592
	Rooftop PV	0.2	25	20	20	0	2840	1974	1364	947	791
South Africa	Utility-scale PV	0.2	25	20	17	0	2400	1625	1062	707	592
	Rooftop PV	0.2	25	20	20	0	2840	1974	1364	947	791
Rest of southern Africa	Utility-scale PV	0.2	25	20	17	0	2400	1626	1062	707	592
	Rooftop PV	0.2	25	20	20	0	2840	1974	1364	947	791
Brazil	Utility-scale PV	0.2	25	20	17	0	1980	1567	1042	707	592
	Rooftop PV	0.2	25	20	20	0	2680	2092	1408	947	791
Mexico	Utility-scale PV	0.2	25	20	17	0	1980	1567	1042	707	592
	Rooftop PV	0.2	25	20	20	0	2680	2092	1408	947	791
Rest of Central America	Utility-scale PV	0.2	25	20	17	0	1980	1567	1042	707	592
	Rooftop PV	0.2	25	20	20	0	2680	2092	1408	947	791
Rest of South America	Utility-scale PV	0.2	25	20	17	0	1980	1567	1042	707	592
	Rooftop PV	0.2	25	20	20	0	2680	2092	1408	947	791

Table A5
Parameter change for sensitivity analysis on the economic potential (<0.15 $\$$ kWh^{-1}).

	–	-	Default	+	++
Interest rate (%)	5%	7.5%	10%	12.5%	15%
Floor to roof area Betas[1]	0.8×	0.9×	1×	1.1×	1.2×
Architectural suitable factor	0.1	0.2	0.32	0.4	0.5
Capital cost Rooftop PV ($\$$ kW^{-1})	0.25×	0.5×	1×	1.25×	1.5×
Solar Irradiance (kWh m^{-2} day^{-1})	0.8×	0.9×	1×	1.1×	1.2×
Performance ratio (%)	75%	80%	85%	90%	95%

[1] *The floor area to roof space conversion betas have been limited to the range of 0–1 to prevent situations of negative roof surface area or roof areas higher than floor space.*

Table A6
Parameter change for sensitivity analysis on the scenario analysis (rooftop PV production (TWh y^{-1}) in 2030).

	–	-	Default	+	++
Cost Curve	0.5×	0.75×	1×	1.25×	1.5×
Whole-sale electricity price	0.5×	0.75×	1×	1.25×	1.5×
Electricity system integration cost	0.5×	0.75×	1×	1.25×	1.5×
Rooftop PV potential	0.5×	0.75×	1×	1.25×	1.5×
Rooftop PV capital cost	0.5×	0.75×	1×	1.25×	1.5×

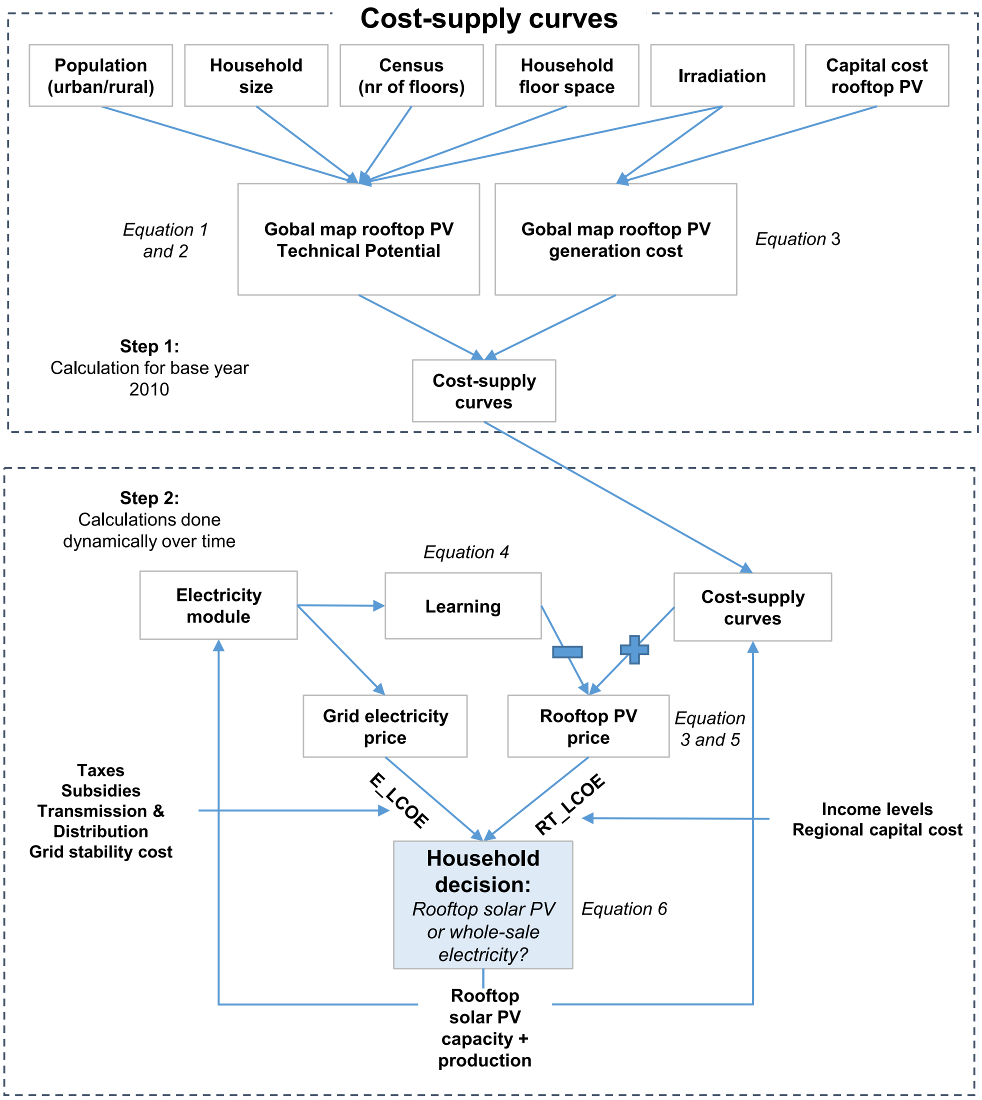

Fig. A1. Flow chart of the overall methodology.

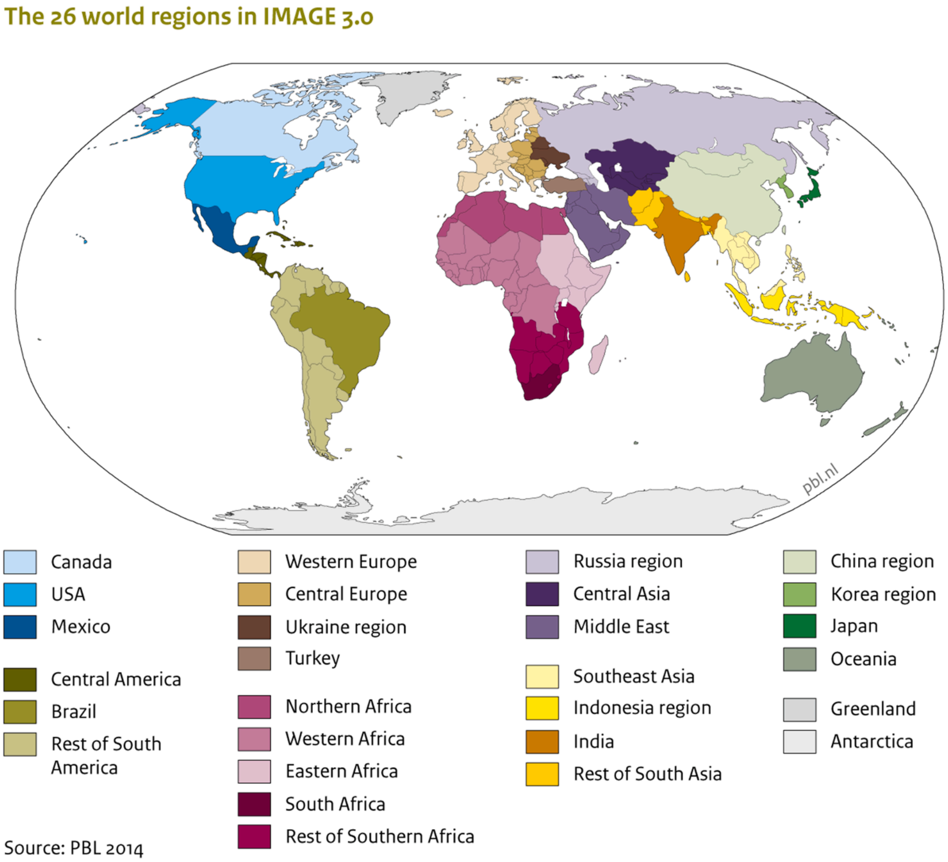

Fig. A2. Region definitions used in IMAGE.

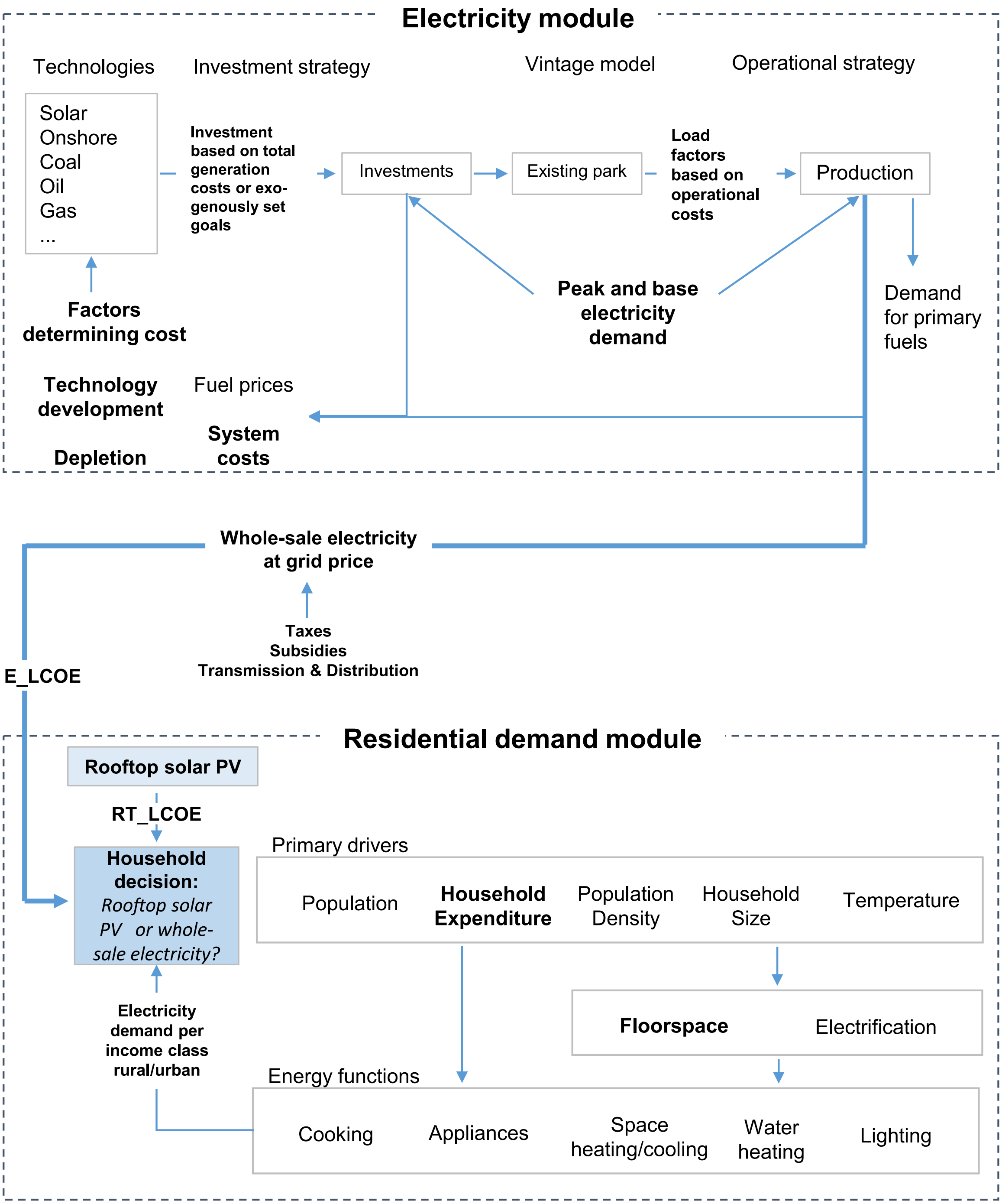

Fig. A3. More complex representation of Fig. 1 (main text) on modelling rooftop PV. See van Vuuren [65] and [26] for details on the electricity module. Daioglou [15] for details on the residential module.

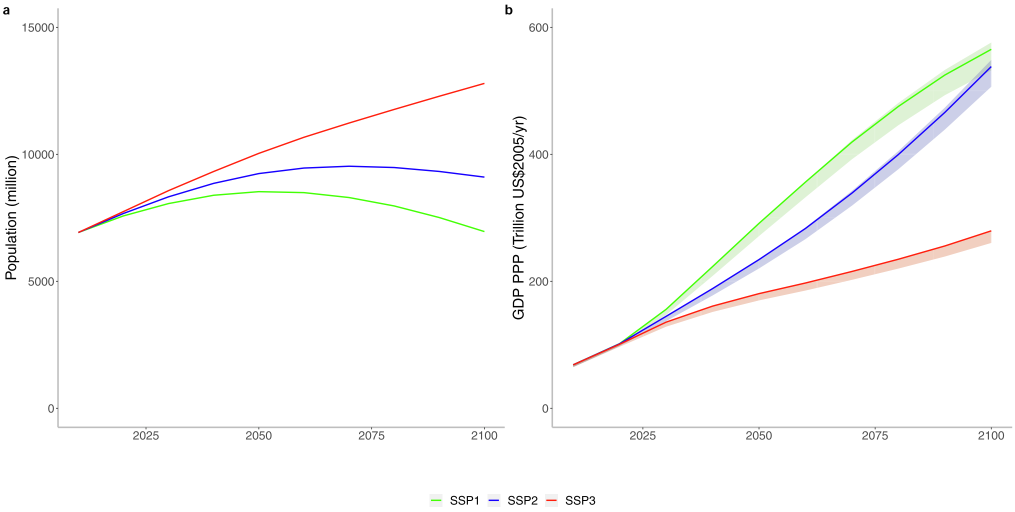

Fig. A4. Global population (left) and economic development (right). The shaded area indicates the range of results of the full set of IAM scenarios for the specific SSP. See Appendix, Text A2 for a detailed explanation of the SSP scenarios.

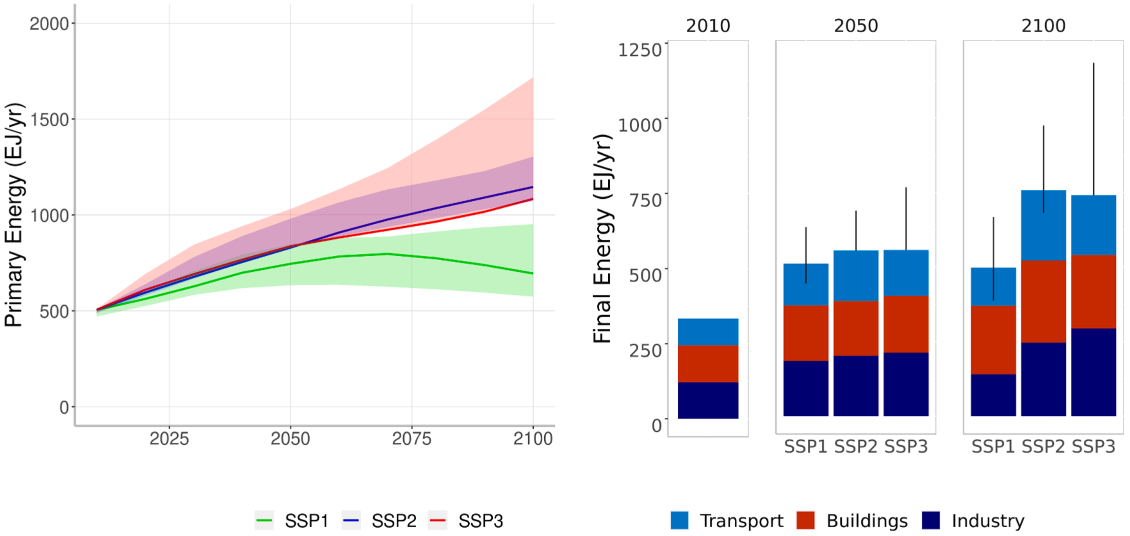

Fig. A5. Primary energy (left) and Final energy (right) development in SSP1, SSP2 and SSP3 scenarios. The shaded areas and the vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP scenario. See Appendix, Text A2 for a detailed explanation of the SSP scenarios.

renewable energies. Investments in education and investments in economic development lead to lower population levels and lower pressures on land. Combined with good governance, adaptation and mitigation to climate change under SSP1 are relatively easy. The SSP3 scenario describes a world of fragmentation; a world with low economic growth, slow technological development and high population growth. Here, both, adaptation and mitigation, are difficult. The SSP2 scenario indicates development pathways under median assumptions(See Tables A1–A6 and Figs. A1–A5).

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