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BROADER PERSPECTIVES

On the role of solar photovoltaics in global energy transition scenarios

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ABSTRACT

The global energy system has to be transformed towards high levels of sustainability in order to comply with the COP21 agreement. Solar photovoltaic (PV) offers excellent characteristics to play a major role in this energy transition. The key objective of this work is to investigate the role of PV in the global energy transition based on respective scenarios and a newly introduced energy transition model developed by the authors. A progressive group of energy transition scenarios present results of a fast growth of installed PV capacities and a high energy supply share of solar energy to the total primary energy demand in the world in the decades to come. These progressive energy transition scenarios can be confirmed. For the very first time, a full hourly modelling for an entire year is performed for the world, subdivided in 145 sub-regions, which is required to reflect the intermittent character of the future energy system. The model derives total installed solar PV capacity requirements of 7.1–9.1 TWp for the electricity sector (as of the year 2015) and 27.4 TWp for the entire energy system in the mid-term. The long-term capacity is expected to be 42 TWp and, because of the ongoing cost reduction of PV and battery technologies, this value is found to be the lower limit for the installed capacities. Solar PV electricity is expected to be the largest, least cost and most relevant source of energy in the mid-term to long-term for the global energy supply.
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KEYWORDS
PV demand; battery demand; energy transition scenario; hourly resolution; 100% renewable energy

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1. MOTIVATION

Further development of human welfare is at a crossroads. For several decades, humankind has needed the capacity of more than one planet Earth [1], and 50% of this need is due to the resource exploitation and emissions of the energy system. Access to (diminishing) energy resources [2] have caused in the past and will cause in the future dramatic economic, social, political and military conflicts. Poverty in the world needs to be tackled [3,4] for a still growing world population [5]. The only pathway to manage all these different major problems is a transition [6] towards a fully sustainable energy system, one that is able to cover accelerated growth in demand for energy.

The two key resources for very large scale renewable energy (RE) harvesting are the wind resource and the direct solar resource. The two major solar technologies are solar photovoltaics (PV) and concentrating solar thermal power (CSP), although the future cost competitiveness of CSP is more and more questioned [7]. Solar PV is the fastest growing energy technology in the world [8] and reached a level of 50 GW of new capacity added annually. Financial renewable energy experts expect installations to grow to 80 GW annually (2020), 143 GW (2030) and 206 GW (2040) [7]. The International Energy Agency (IEA) lags behind by projecting annual installations of 37.1 GW (2013–2020), 32.6 GW (2020–2025), 33.6 GW (2025–2030), 34.4 GW (2030–2035) and 33.2 GW (2035–2040) in its New Policies Scenario [9,10], which is not only in

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contradiction to the already achieved level of installations of 50 GW in 2015 [11] and the expectation of 60 GW in 2016 and 70 GW in 2017 [12], but also to the fact that solar PV has become the least cost source of electricity in a fast growing number of regions in the world [13–16]. IEA scenarios have a more than 20-year track record of being fully incompatible with real world PV installations [17], and the IEA has continuously failed to catch up with the level of insights of other institutions.

The two observations, that solar PV is the fastest growing energy technology in the world and the highly blurry view of international institutions on the future of solar PV, led us to the following research question discussed in this paper: What is the mid-term to long-term solar PV demand in a world based on sustainable energy resources?

For us to answer this question, a two-step approach, as explained in Section 2, is applied. The role of solar PV in the major energy transition scenarios is reviewed in Section 3. Based on modelling results of Lappeenranta University of Technology (LUT), the role of solar PV in the financial assumptions of the year 2030 is investigated and summarised in full hourly resolution on a global level for the very first time in Section 4. The LUT results are discussed in comparison with the major energy transition scenarios, and an outlook is provided in Section 5. The conclusions related to the research question are summarised in Section 6.

2. METHODOLOGY

This section is subdivided into the methodology for reviewing the global energy transition scenarios (Section 2.1) and introducing the LUT Energy system model (Section 2.2).

2.1. Review of global energy transition scenarios

An overview of the major global energy scenarios for the years 2030, 2050 and 2100 is compiled, and the role of PV is extracted from these benchmarking publications. As far as possible, the total installed capacity numbers are extracted, as well as the solar PV supply share of the total primary energy demand for the power sector and the total energy system. The scenarios are taken from Bloomberg New Energy Finance (BNEF) [7], Greenpeace [18], International Energy Agency (IEA) [9], Photovoltaic Power Systems Programme of the IEA (IEA-PVPS) [19], International Renewable Energy Agency (IRENA) [20], World Wildlife Fund (WWF) [21], International Institute for Applied Systems Analysis (IIASA) Global Energy Assessment (GEA) [22], Intergovernmental Panel on Climate Change (IPCC) [23], German Advisory Council on Global Change (WBGU) [24], Jacobson and Delucchi [25] and Shell [26]. Massachusetts Institute of Technology [27], BP [28] and Exxon Mobil Corp. [29] had to be excluded because of no disclosed PV numbers along with very small supply shares for renewables.

2.2. Lappeenranta University of Technology energy system model

The LUT Energy system model [30] is based on linear optimisation of energy system parameters under previously defined constraints applied to the system. Assumptions for future RE power generation and demand and required storage technologies are also considered. Additional water desalination and synthetic natural gas (SNG) generation are the flexible demands in the model and, therefore, can substitute some storage capacities. One of the key constraints for the system optimisation is the matching of power generation and demand on an hourly basis for a particular year. The main aim of the system optimisation is the minimisation of the total annual energy system costs, which are a sum of the annualised costs of the installed capacities of the different technologies, additional costs of energy generation and generation ramping. Also, the system consists of prosumers for residential, commercial and industrial sectors. The prosumers instal the respective capacities of rooftop PV systems and batteries. Minimising the cost of consumed energy is the main aim of the target function for the prosumers. Electricity prices for residential, commercial and industrial consumers for all the countries are taken from Gerlach *et al.* [31]. The electricity prices for 2030 are calculated according to the assumptions from Gerlach *et al.* [31] that grid electricity prices rise by 5% per annum for <0.15 €/kWh, by 3% per annum for 0.15–0.30 €/kWh and by 1% per annum for >0.30 €/kWh. The excess electricity generated by the prosumers is assumed to be fed into the grid for a transfer selling price of 2 €cents/kWh. The flowchart of the model is presented in Figure 1.

A detailed description of the model can be found in Bogdanov and Breyer [30]. Detailed information of the input data used for the model is given in Bogdanov and Breyer [30] and additional calculations related to geothermal energy potential, desalination water demand [32] and industrial gas demand data are described in [33].

The technologies used for converting RE sources into electricity are two different types of ground mounted PV systems (optimally tilted and single-axis north–south oriented horizontal continuous tracking) and rooftop PV, concentrating solar thermal power (CSP), onshore wind turbines, hydro power (run-of-river and dams), biomass (biogas and solid biomass), waste-to-energy power plants and geothermal power plants.

The energy storage technologies used in the model are residential and system-level battery storage, pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and power-to-gas (PtG) technology. Technologies such as water electrolysis, methanation, CO_2 scrubbing from air, gas storage, and both combined and open cycle gas turbines are part of the synthesis of SNG and its reconversion to electricity.

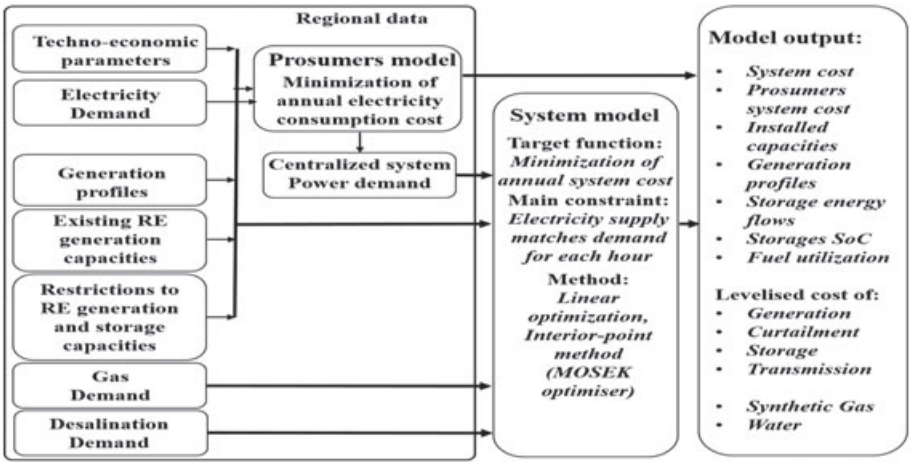

Figure 1. Model flow diagram with the input data, system model optimisation and output data. RE, renewable energy; SoC, state of charge.

The PtG technologies have to be operated in synchronisation because of the absence of hydrogen and CO_2 storage. There is a 48-hour biogas buffer storage and part of the biogas can be upgraded to biomethane and introduced to the gas storage.

The bridging technologies used in this model provide the required flexibility to the energy system and help in reducing the overall cost. For example, gas produced from PtG can be used for industrial gas demand rather than stored for electricity sector. Similarly, seawater reverse osmosis desalination couples the water sector with the electricity sector.

The power transmission within the sub-regions is assumed to be based on alternating current (AC) grids which are not included in the model, and between the sub-regions on high voltage direct current (HVDC). Loss of electricity proportional to the length of the transmission lines and in converter stations at the interconnection with the AC grid form a major component of the power losses in HVDC grids.

The full block model diagram is presented in Figure 2.

The feed-in profiles for solar technologies were calculated based on NASA data [34,35] for direct and diffuse solar irradiation, wind speed and temperature for the year

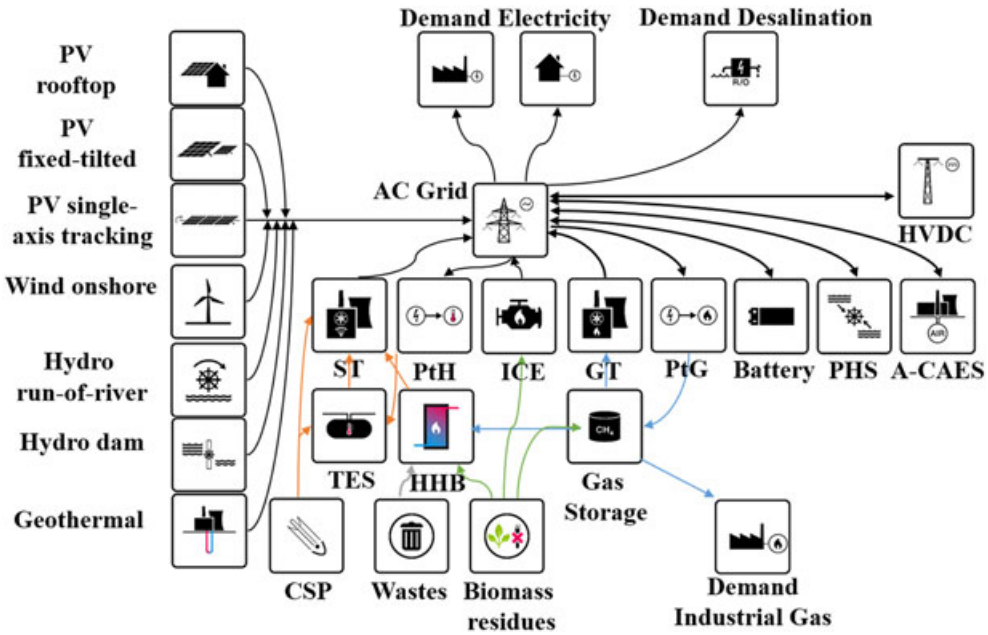

Figure 2. Block diagram of the all the energy technologies applied in the Lappeenranta University of Technology Energy system model. AC, alternating current; A-CAES, adiabatic compressed air energy storage; CSP, concentrating solar thermal power; GT, gas turbine; HHB, hot heat burner; HVDC, high voltage direct current; ICE, internal combustion engine; PHS, pumped hydro storage; PtG, power-to-gas; PtH, power-to-heat; PV, photovoltaic; ST, steam turbine; TES, thermal energy storage.

2005 reprocessed by the German Aerospace Center [36]. The financial and key technical assumptions for all applied technologies are tabled in the Appendix and explained in more detail in Bogdanov and Breyer [30]. The assumed solar PV operational expenditures (Opex) may be more ambitious than the capital expenditures (Capex); however, the Opex which could be achieved in Germany in 2015 has been reported [37] to be already lower than that assumed for the year 2030 as a global average in this research, and the realised Opex cost reductions in the years 2011–2015 were about 15%/a [37], whereas only about 5%/a are needed to achieve the cost level assumed in this research. A sensitivity analysis shows that a 0.1% absolute increase of annual Opex as a percentage of Capex leads to about 1% higher PV levelised cost of electricity (LCOE). Weighted average cost of capital (WACC) is set to 7% for all scenarios, but for residential PV prosumers WACC is set to 4% because of lower financial return requirements.

The results of the energy system analyses are based on 100% renewable energy (RE) and are integrated on a global scale for the very first time. The key advantage of the LUT results is the hourly modelling of the energy system for an entire year based on RE resource data for solar, wind and hydro on a high spatial resolution of 0.45° × 0.45° or higher and consequent solving of a least cost target function. None of the benchmarking energy scenarios are performed on an hourly resolution for an entire year [38]. However, this is of high importance because an energy system mainly based on PV and wind energy is characterised by a high degree of intermittency. The results are based on three scenario set-ups, which reflect geographic integration and sectorial integration:

- region-wide: rather distributed; no energy exchange between neighbouring sub-regions allowed; electricity sector
- area-wide: distributed and centralised system; electricity trade among all sub-regions within a major world region allowed without any limitations; electricity sector
- integrated: distributed and centralised system; electricity trade among all sub-regions within a major world region allowed without any limitations; electricity, industrial gas and desalination sectors

The world had been subdivided into 145 sub-regions, which are used as building blocks for different setups of modelling. The main focus of research has been so far to aggregate the 145 sub-regions into nine major world regions, which form the main body of the results of this paper. Other research aggregates the sub-regions, so that an integrated analysis can be carried out for Europe-Eurasia-MENA [39] and East Asia [40], all in full hourly resolution and interconnected. The nine major world regions are: Europe [41], Eurasia [42], Middle East Northern Africa (MENA) [43], Sub-Saharan Africa [44], India/SAARC [33], Northeast Asia [30], Southeast Asia and the Pacific Rim [40,45], North America [46] and South America [47]. Solar PV is represented in the model by ground-mounted optimally tilted and single-axis tracking PV power plants and prosumer rooftop systems, enhanced by batteries in the cases of financial attractiveness for the prosumers.

3. REVIEW OF GLOBAL ENERGY TRANSITION SCENARIOS

The results for the energy transition scenarios are summarised in Table I. The expected global PV capacities range from 950–3725 GWp (2030), 1405–6678 GW (2040), 6745–32 700 GWp (2050) and 32 700–133 000 GWp (2100). The large ranges clearly indicate that there is no consensus on the expected capacities. The range in solar PV electricity contribution to the total electricity demand is 4.1%–15.9% (2030), 5.5%–18.2% (2040) and 19.9%–29.0% (2050), whereas the findings for 2050 cannot be compared with 2030 and 2040 because only two progressive scenarios provided respective numbers for 2050. Notably, the World Energy Outlook (WEO) of the IEA sets in all cases the minimum expectation, which has been already criticised in the past [10,17,48–51]. The IEA claimed in its latest WEO to better reflect renewable energy deployment [9]; however, this does not withstand a fact check [52]. The IEA has not closed the gap in its PV insights compared with all other scenario makers even though the IEA should have excellent access to all energy-related information globally. The share of solar PV in the global electricity supply in the year 2050 is expected by Greenpeace to be about 20%, which is surprisingly low, and by WWF to be about 30%, which remains also moderate given the fact that solar PV is already in the mid-2010s—the least cost source of electricity in a fast growing number of regions around the planet.

More interesting is the discussion of the findings on the share of solar energy in global energy supply. It should be discussed first why this is the key metric for the overall assessment of the scenarios. First of all, most selected scenarios provide information for the share of solar energy in the total energy supply. Second, the shift to power megatrend moves electricity generation to the centre of the energy system [53]. Finally, nearly all energy sectors will be based on electricity, such as electricity-based heating (e.g. electric heat pumps), electricity-based mobility (e.g. electric vehicles, electricity based synthetic fuels [54,55]) and electricity-based chemicals [56]. This megatrend is driven by the efficiency increase of the electricity-based solutions, the fast cost decline of renewable-based electricity solutions and the increasing pressure to factor in the full societal costs. Hence, the electricity-based solutions become more competitive in almost all energy sectors. How long this shift to power megatrend will need to cover most of the total primary energy demand (TPED) as of the mid-2010s is not yet certain, but by the middle of 21st century, the transition should be mainly finished. Remaining non-electric energy sources are mainly geothermal energy and

Table I. Benchmarking global energy transition scenarios and the respective role of solar PV. Abbreviations: total primary energy demand, *TPED*, and electricity, *elec*. The colour code indicates the role for solar PV as follows: little (red), moderate (orange) and substantial (green).

		PV capacity				share PV on TPED-elec			share solar total on TPED-all			
		2030	2040	2050	2100	2030	2040	2050	2030	2040	2050	2100
	[Ref]	[GWp]	[GWp]	[GWp]	[GWp]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
BNEF	[7]	1799	3687			7.7%	14.3%					
Greenpeace - ER	[18]	2839	4988	6745		11.4%	16.5%	19.9%	6.1%	14.1%	22.2%	
Greenpeace - Adv ER	[18]	3725	6678	9295		13.7%	18.2%	20.2%	7.7%	18.4%	29.1%	
IEA - NPS	[9]	949	1405			4.1%	5.5%		0.8%	1.2%		
IEA - 450	[9]	1278	2108			6.0%	9.4%		1.1%	2.5%		
IEA-PVPS	[19]	1570	3930	11010	133000				0.7%	1.4%	3.3%	25.3%
IRENA REmap - mix	[20]	1760				15.9%		16.7%	17.0%		22.0%	
IRENA REmap - doubling	[20]	2520						21.7%			29.0%	
WWF	[21]					7.6%	16.3%	29.0%	7.1%	17.8%	30.6%	
IIASA-GEA - Efficiency	[22]								6.9%		23.7%	
IIASA-GEA - Mix	[22]								7.7%		20.6%	
IIASA-GEA - Supply	[22]								9.0%		17.0%	
IPCC - 5th AR WGIII - MESSAGE	[23]								6.4%	12.9%	15.3%	42.8%
IPCC - 5th AR WGIII - REMIND	[23]								0.4%	2.3%	6.6%	40.3%
IPCC - 5th AR WGIII - GCAM	[23]								0.4%	1.1%	1.3%	2.7%
WBGU	[24]								4.0%	10.6%	27.7%	66.9%
Jacobson and Delucchi	[25]	32700	32700	32700	32700						40.0%	40.0%
Shell - Mountains	[26]								1.5%	2.4%	3.6%	37.7%
Shell - Oceans	[26]	1800		20000					3.2%	8.2%	13.6%	
min		950	1405	6750	32700	4.1%	5.5%	19.9%	0.8%	1.1%	1.3%	2.7%
max		3730	6680	32700	133000	15.9%	18.2%	29.0%	9.0%	18.4%	40.0%	66.9%
average		2027	3799	15950	82850	9.5%	13.4%	21.5%	5.0%	7.7%	19.1%	36.5%

biomass, the latter of which is limited and has to fulfil sustainability criteria. Fossil fuels are not compatible with the COP21 targets and carbon capture and storage (CCS) may never be profitable [57]. Nuclear energy violates all sustainability criteria [18,21,24] and thus needs to be phased-out. The solar energy technologies may be finally represented by solar PV, because solar thermal collectors for heating are higher in cost than the solar PV plus heat pump alternative [58]. Furthermore, CSP plants cannot catch up anymore with solar PV power plants, as indicated by extremely low market expectations of the market research analysts of BNEF [7], and also by recent research [59]. CSP could still have a chance, because the low-cost thermal energy storage and the secured capacity of the steam turbine are very valuable, but very high growth rates would be required to compensate for the comparably low learning rate of 10–12% for CSP [60] as compared with a 20–23% rate for PV modules [61–63] and about a rate of 16% for total PV systems [63] to reduce the cost gap for solar PV [60]. Challenging for CSP are hybrid PV-battery-GT plants, which are expected to be financially attractive in the 2020s [59], because these new hybrid PV plants are technically fully comparable with CSP and, depending on the cost development of battery storage, they may become highly attractive. This is rather likely due to the high learning rates of batteries, which are around 20% [64,65], and the very high growth rates, which reduce the cost currently on a 10–20% rate per year [65]. As a consequence, the probability is high that in the year 2050, the solar energy technologies are dominated by solar PV.

The solar energy share in TPED range in the regarded energy transition scenarios is 0.8–%9.0% in 2030, 1.1%–18.4% in 2040, 1.3%–40.0% in 2050 and 2.7%–66.9% in 2100. Two of the three major energy scenarios for the IPCC fifth assessment report belong to the most conservative scenarios. This is surprising because solar PV would offer an excellent opportunity to fight climate change. However, an analysis of the cost assumptions in the scenarios for solar PV, used in respective publications in the year 2014, reveals fully outdated cost assumptions for 2050, with 1000–2100 USD/kWp (770–1615 €/kWp[1]) and 1250 USD/kWp (962 €/kWp[1]) for REMIND and GCAM, respectively [66]. The capital expenditure for the year

[1]USD/€ exchange rate of 1.30, which is the long-term average, as well as the average of the years 2012–2014 when the source article had been submitted and published

2016 is around 700 €/kWp for India [67] and China, and in Germany and Denmark around 850 €/kWp, as also documented by recent tenders [68]. The higher capital expenditures in Germany are mainly explained by the anti-dumping and anti-subsidy duties on imports of PV modules from China in Europe. Two of the leading scenarios for the IPCC energy system modelling are based on fully outdated cost assumptions. The consequence is that, compared with industry-related cost insights for 2050 of 320–400 €/kWp [69], a difference of factors of about 1.9–4.9 needs to have a dramatic impact on the role of solar PV in the IPCC energy system scenarios. Keeping in mind that the IPCC has been recently invited to conduct an assessment of the 1.5 °C scenario [70], the authors of this paper strongly recommend correcting the outdated PV cost assumptions in the IPCC energy system scenarios as soon as possible. However, the MESSAGE model also used for IPCC energy system modelling showed much better results. Because the IPCC reports are mainly based on peer-reviewed publications, a delay of up to 2 years of most recent information in the reports may occur. The requested assessment of the 1.5 °C scenario offers a new opportunity for the IPCC to integrate the latest solar PV cost insights published in peer-reviewed papers, governmental reports, such as [67] and also by leading financial analysts. Schellnhuber *et al.* [71] encouraged the IPCC researchers to take into account the fast cost reductions of renewables and in particular solar PV for achieving a more rapid scale up in the IPCC scenarios to better reflect the observed exponential growth and respective cost decline. Consequently, it has been grouped in the moderate group. The IEA scenarios belong again to the most conservative scenarios for the years 2030 and 2040.

The share of solar energy supply of the TPED in the progressive scenarios reaches about 18% for 2040, and are typically 20–30% for 2050, with the exception of Jacobson and Delucchi [25], who expect around 40%. Most interesting is the expected share of solar PV for the year 2100, which reaches values of 40% and higher for the two IPCC models (MESSAGE and REMIND), Jacobson and Delucchi and remarkably 67% for the WBGU [24] scenario from the year 2003. Even the Shell Mountains scenario is close to 40%. The authors of this paper find the first indications that the optimistic findings for the year 2100 of the progressive scenarios may be more realistic in the middle of the 21st century, because of the very fast and steep cost decline of solar PV and supporting technologies, which will be discussed in more detail in the next section.

Summing up, the energy transition scenarios can be grouped into rather progressive ones and rather conservative ones. The progressive studies are: BNEF [7], Greenpeace [18], WBGU [24], IEA-PVPS [19], IRENA [20], WWF [21], IIASA GEA [22] and Jacobson and Delucchi [25]. The conservative ones are: IEA WEO [9], IPCC [23] and Shell [26]. It needs to be mentioned again that Massachusetts Institute of Technology [27], BP [28] and Exxon Mobil Corp. [29] studies had to be excluded because of no disclosed PV numbers along with very small supply shares for renewables. Shares of solar PV in the power sector are up to about 14% (2030), 18% (2040) and 29% (2050); and the shares of solar energy in the energy system are expected to be up to about 9% (2030), 18% (2040), 40% (2050) and 67% (2100).

4. 100% RENEWABLE ENERGY SYSTEM MODELLING BY LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

The results of the LUT energy system model simulations for 100% RE for the weather year 2005, the cost and demand assumptions for the year 2030, and the integrated scenario are depicted as a global overview in Figure 3. More detailed results are shown for all 145 sub-regions globally aggregated for the nine major world regions: Northeast Asia, Southeast Asia and India/SAARC (Figure 4), Europe and Eurasia (Figure 5), MENA and Sub-Saharan Africa (Figure 6) and North America and South America (Figure 7). Detailed information on all 145 sub-regions can be found in the respective publications [30,33,40–47] and in an online publication visualising the hourly supply, demand, trading and storage charge and discharge for all 145 sub-regions and the nine major world regions [72].

The mentioned assumptions lead to a global cumulated PV demand of 9.1 TWp (region-wide), 7.1 TWp (area-wide) and 12.0 TWp (integrated) for 2030 data (Tables II and III, Figures 3–7). The share of the prosumer driven PV capacity is found to be between 31–52% on average globally depending on the applied scenarios, reaching 3.7 TWp in total. The shares of the fixed tilted plants of the total ground mounted utility-scale PV power plants are found to be 28% (region-wide), 6% (area-wide) and 2% (integrated) on average globally.

The energy contribution share of PV to the total energy demand is found to be 36–42% on average globally, reaching around 14 900 TWh/a (region-wide), 11 950 TWh/a (area-wide) and 21 670 TWh/a (integrated). The area-wide scenario is characterised by a full interconnection of all sub-regions within a major world region. This leads to a more efficient utilisation of all system components in general, but also to a better integration of the more volatile wind resources, both leading to a reduction in PV capacities and generation. The global average of the solar PV electricity share is 42% (region-wide), 36% (area-wide) and 41% (integrated). The three regions with the highest fraction of solar PV electricity in the supply for the integrated scenario are Northeast Asia, Southeast Asia and India/SAARC, all between 48–51% and representing slightly more than half of global population. The lowest contribution share is found in Eurasia, because prosumer PV obtains the lowest share due to highly subsidised electricity prices and excellent wind resource availability. In general, it can be stated that solar PV is complemented

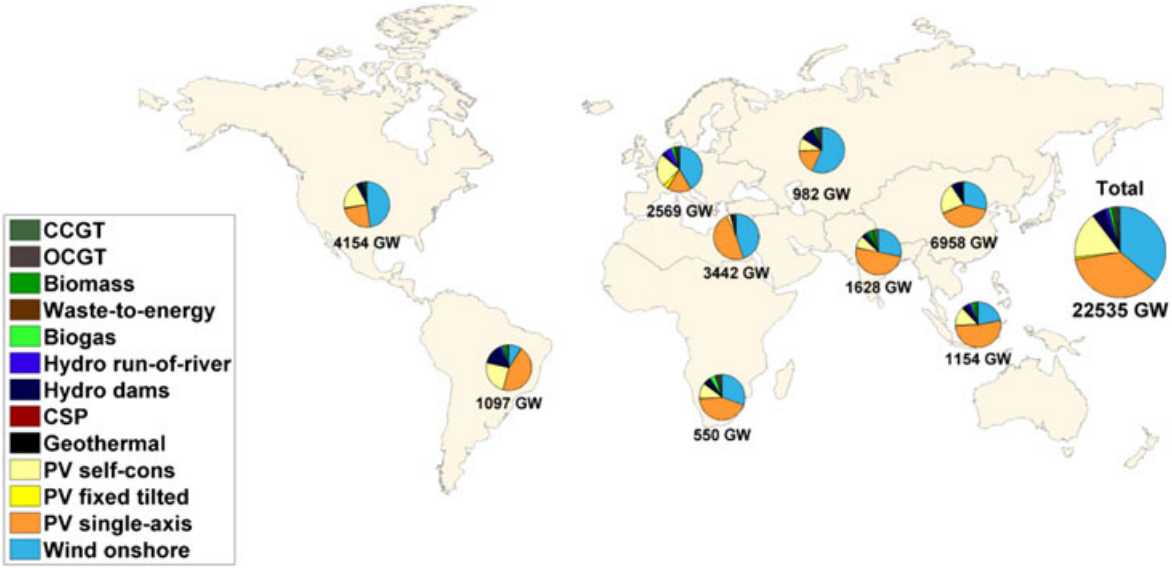

Figure 3. Installed capacities for the integrated scenario in a global overview structured in the nine major world regions: Northeast Asia, Southeast Asia, India/SAARC, Eurasia, Europe, MENA, Sub-Saharan Africa, North America and South America. Data are taken from [30,33,40–47], which are visualised in more detail in Figures 4–7 and by the Internet of Energy online visualisation tool [72]. CCGT, combined cycle gas turbines; CSP, concentrating solar thermal power; OCGT, open cycle gas turbines; PV, photovoltaic.

quite well by wind energy, as already found earlier by Gerlach *et al.* [73], but also by hydro power, in particular hydro dams, because they act as virtual batteries balancing solar PV and wind generation. This is shown best for the case of Brazil [74], but also more flexible biomass power plants balance the resource fluctuations of solar PV and wind energy.

Fluctuations that cannot be balanced by flexible generation or by the geographic integration function of grids are balanced by storage. The most relevant storage technology is batteries, because they provide 63% (region-wide), 69% (area-wide) and 75% (integrated) of all stored electricity (Table IV and Figure 8). The remaining storage demand is covered by pumped hydro storage, which is operated in a very similar manner as batteries, A-CAES and seasonal PtG storage. A-CAES shows its economically optimised value add-in weekly storage and corresponds, because of weekly resource fluctuations, best to wind energy. It had been observed that geographic integration (area-wide) substitutes A-CAES almost completely, because within continental grids the wind resource fluctuations do not occur in the total continental area, and therefore can be balanced by continental grids. This effect is discussed in more detail in Gulagi *et al.* [75]. For seasonal balance hydro dams are well suited as well as PtG storage. The global PtG capacity demand for seasonal storage is found to be 450 GW_{el} for the region-wide, rather decentralised scenario approach, and this demand shrinks drastically to 242 GW_{el} for the area-wide, more centralised scenario approach. The PtG capacities in the integrated scenario increase substantially to 2093 GW_{el}, which is a consequence of industrial gas demand, because it is assumed that industrial gas demand cannot be supplied anymore by fossil natural gas in a 100% RE system. Instead, this demand is supplied by biomethane and RE-based PtG. Seasonal storage for the power system is then a by-product of the large industrial gas capacities, as qualitatively already expected by Agora Energiewende [76] and now confirmed in a quantitative analysis. PtG provides with methane (CH_4) a second major energy carrier for the energy system, besides the dominating electricity. Hydrogen (H_2) is not used as an energy carrier, but an intermediate form of chemical energy. The overall storage demand, measured in electricity provided by storage in relation to the electricity demand is found to be 19% (region-wide), 14% (area-wide) and 10% (integrated). This is tabled in more detail for the nine major world regions in Table IV. This means that most of the generated electricity is used directly without storing it, and the geographic distribution of large interconnected grids reduces the storage demand by about 25% (relative). However, sector integration (here with desalination and industrial gas demand) further reduces the storage demand by slightly less than 30% (relative). Continental grids provide flexibility for the energy system in the geographic dimension, whereas a sector integration provides flexibility in the temporal dimension.

The total battery storage capacities are 11.4 TWh_{el} (region-wide), 9.1 TWh_{el} (area-wide) and 9.9 TWh_{el} (integrated). The respective shares of prosumer PV battery to the total battery capacities are 44% (region-wide), 54% (area-wide) and 50% (integrated), that is, around half of the global stationary battery demand is driven by prosumer PV end-users. The relevance of storage and in particular battery storage is compared with grid exchange among

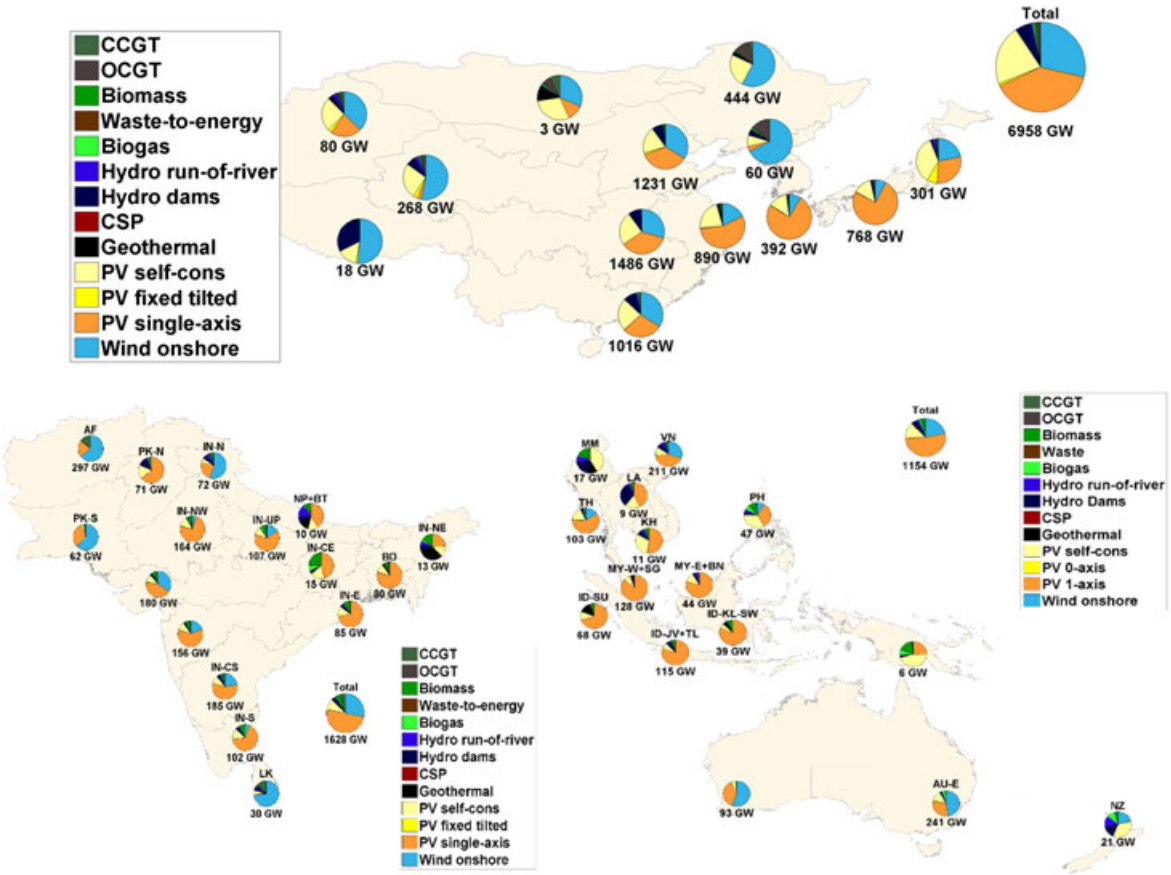

Figure 4. Installed capacities for the integrated scenario for Northeast Asia (top) [30], India/SAARC (bottom left) [33] and Southeast Asia and the Pacific Rim (bottom right) [45]. The hourly visualisation is provided by the Internet of Energy online visualisation tool [72]. CCGT, combined cycle gas turbines; CSP, concentrating solar thermal power; OCGT, open cycle gas turbines; PV, photovoltaic.

the sub-regions and presented in more detail in Table IV. The contribution of storage to covering the demand by storage is visualised in Figure 8. More details on the strong correlation of the solar PV share and the demand coverage share of batteries can be found in Bogdanov *et al.* [77].

The LUT Energy system model is further developed in its functionality, but for the results presented in this paper about 45% of the total primary energy demand is covered in the integrated scenario. On this basis, the results can be roughly extrapolated to estimate the total PV capacity demand, which is found for the year 2030 assumptions to be 27.4 TWp, because the integrated scenario covers roughly 45% of TPED (not yet included are the sectors: heating, mobility, industry and others). Already now, these findings can be further extrapolated to estimate the long-term PV demand (for the year 2100) based on 10 billion people on planet Earth and a per capita demand equal to current levels in Europe. This leads to about 42.3 TWp, and represents a solar PV supply share of roughly 45% of TPED.

A further key result of the LUT Energy system model are the costs of the energy system. These costs are not presented in detail here, because the energy transition scenarios do not present the costs in much detail, neither the input assumptions of the technology cost nor on the output cost of the system. Some scenarios give some insights, but detailed information is missing for all scenarios. Nevertheless, the LUT Energy system model delivers detailed cost results, which are presented in summary in Table III and in more detail in the respective publications for the nine major world regions [30,33,40–47]. One of the most interesting results of the 100% RE system modelling with 2030 assumptions is the low cost of the energy systems around the world. Part of the cost calculation is the levelised cost for generation, storage, curtailment and HVDC power lines summarised in the total levelised cost, based on capital expenditures, operational expenditures, lifetimes, fuel cost for biomass, technical efficiencies and cost of capital. The calculation of the levelised cost is presented in more detail in Bogdanov and Breyer [30]. The global demand weighted average costs are for the region-wide scenario 65 €/MWh (range of 58–72 €/MWh), for the area-wide scenario 58 €/MWh (range of 53–67 €/MWh) and the integrated scenario 49 €/MWh (range of 42–64 €/MWh) as

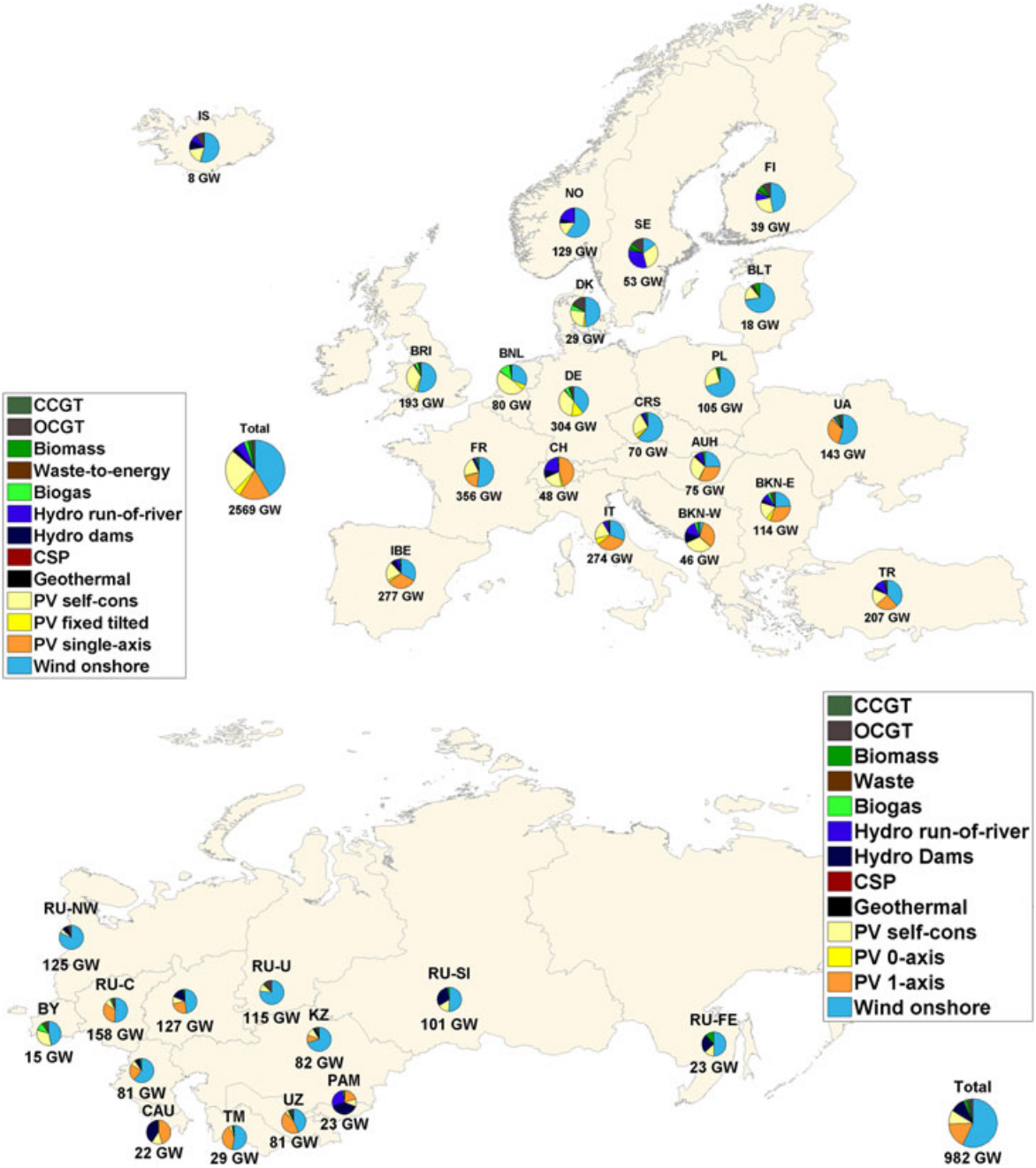

Figure 5. Installed capacities for the integrated scenario for Europe (top) [41] and Eurasia (bottom) [42]. The hourly visualisation is provided by the Internet of Energy online visualisation tool [72]. CCGT, combined cycle gas turbines; CSP, concentrating solar thermal power; OCGT, open cycle gas turbines; PV, photovoltaic.

summarised in Table III. The cost digression from region-wide to area-wide is due to more efficient use of all system components because of geographic flexibility provided by the grid interconnection of sub-regions. The further cost digression from the area-wide to the integrated scenario is due to the provided flexibility of the sector coupling, in particular because the SNG production delivers seasonal storage more or less as a by-product of the industrial gas supply. The electricity trading among the sub-regions is on average globally about 14% of the total demand in the integrated scenario (and similar in the area-wide scenario), which implies that the 100% RE system solution shows a strong, decentral, and distributed structure. Solar PV electricity is typically not traded among the sub-regions, because the solar resource is quite evenly distributed and roughly accessible in the same hours. In addition,

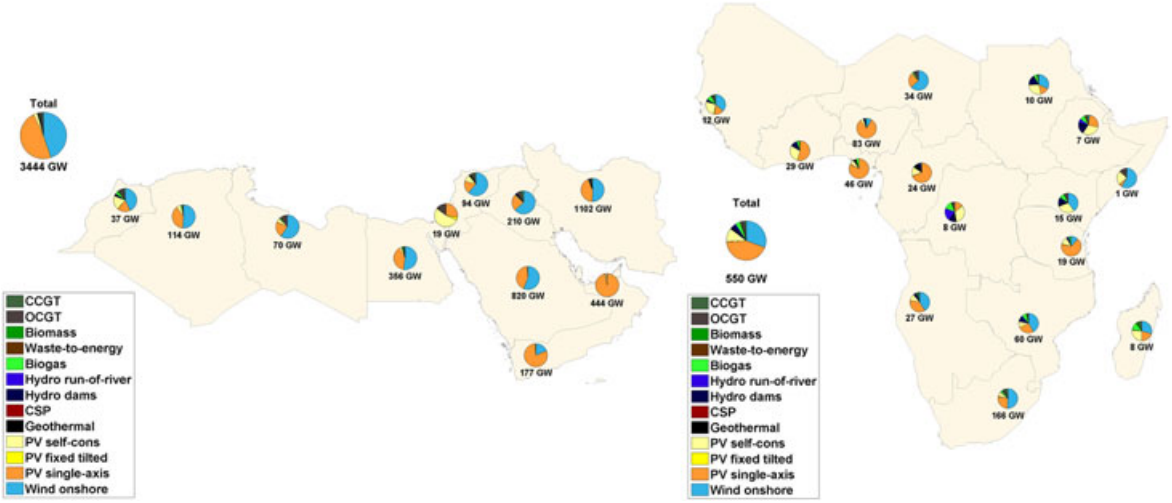

Figure 6. Installed capacities for the integrated scenario for MENA (left) [43] and Sub-Saharan Africa (right) [44]. The hourly visualisation is provided by the Internet of Energy online visualisation tool [72]. CCGT, combined cycle gas turbines; CSP, concentrating solar thermal power; OCGT, open cycle gas turbines; PV, photovoltaic.

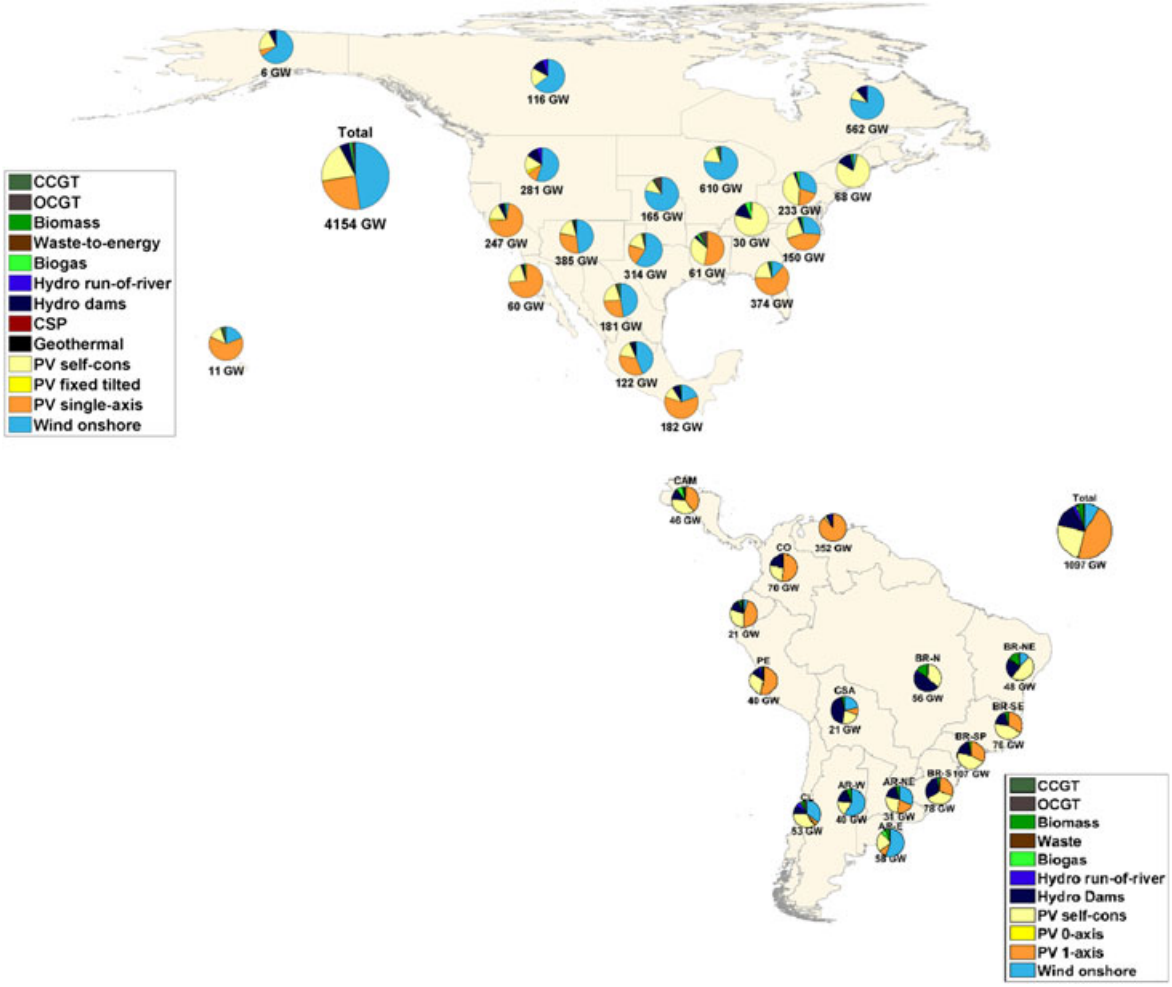

Figure 7. Installed capacities for the integrated scenario for North America (top) [46] and South America (bottom) [47]. The hourly visualisation is provided by the Internet of Energy online visualisation tool [72]. CCGT, combined cycle gas turbines; CSP, concentrating solar thermal power; OCGT, open cycle gas turbines; PV, photovoltaic.

Table II. Global solar photovoltaic (PV) demand subdivided by the nine major world regions of the world.

	Population 2030	Electricity demand 2030	Electricity demand 2030	PV prosumer	PV plants	PV total	PV electricity	PV share
Integrated		Electricity	Integrated					
	[mil]	[TWh]	[TWh]	[GW_p]	[GW_p]	[GW_p]	[TWh]	[%]
Northeast Asia	1546	9878	13 496	1509	2806	4315	6986	48
Southeast Asia	646	1630	2635	150	609	758	1425	51
India/SAARC	1922	2597	3376	145	815	960	1880	50
Eurasia	244	1450	2550	92	171	263	388	15
Europe	675	4183	5127	608	353	991	1384	27
MENA	529	1813	7917	85	1668	1755	4098	49
Sub-Saharan Africa	1384	866	1223	61	241	302	636	48
North America	558	6059	10 304	812	1038	1850	3452	32
South America	445	1813	2780	268	496	764	1419	48
World	7949	30 289	49 408	3730	8197	11 958	21 668	41
				31%	69%			

Data are based on [30,33,40–47] and visualised in more detail in Figures 3–7, with updated results for Northeast Asia based on latest assumptions for all major world regions.

Table III. Key parameters of the 100% RE systems subdivided by the nine major world regions in the world.

Regions	LCOE region-wide	LCOE area-wide	Integration benefit **	Storage*	Grids regional trade*	Curtailment	PV*	Wind*	Biomass*	Hydro*
	[€/MWh]	[€/MWh]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Northeast Asia	63	56	6.0	12	10	5	48.1	37.9	3.0	10.8
Southeast Asia	67	64	9.5	11	3	3	44.0	22.0	22.9	7.6
India/SAARC	72	67	5.9	19	23	3	49.7	32.1	10.9	5.4
Eurasia	63	53	23.2	5	13	3	13.7	58.1	13.0	15.4
Europe	73	64	8.7	8	15	2	27.2	55.0	6.6	9.3
MENA	61	55	10.8	11	10	5	48.2	48.4	1.3	1.1
Sub-Saharan Africa	58	55	16.2	9	10	4	50.3	31.1	7.8	8.2
North America	63	53	10.1	6	24	4	30.8	58.4	3.7	6.8
South America	62	55	7.8	7	8	5	40.1	10.8	28.0	21.1
World	65	58	9	10	14	4	41.1	43.7	6.8	8.4

Data are based on [30,33,40–47] and visualised in more detail in Figures 3–7, with updated results for Northeast Asia based on latest assumptions for all major world regions. Superscripts: * integrated scenario, supply share and ** annualised costs. PV, photovoltaic; RE, renewable energy.

transmission over many thousands of kilometres has been found to be not economical attractive, mainly because of the cost competitiveness of local storage [30,40,45,78].

5. DISCUSSION

The key results of the LUT Energy system modelling are a PV capacity demand of 7.1–9.1 TWp when considering the power sector only and 12.0 TWp for the integrated scenario, representing about 45% of TPED for year 2030 assumptions. The share of solar PV electricity of the total generation is about 41%. The extrapolation to the full energy system leads for 2030 assumptions to 27.4 TWp and for an expected demand in the year 2100 to 42.3 TWp.

This can be compared with the findings of the major energy transition scenarios. In capacity units for the year 2040 and 2050, comparable numbers for 2040 are only presented by the Greenpeace Energy [R]evolution [18] scenarios with 5.0 and 6.7 TWp. IEA WEO [9] projections, at 1.4 and 2.1 TWp, are most conservative compared with other scenarios. Jacobson and Delucchi [25] also describe a

Table IV. Demand coverage by grid exchange among sub-regions and storage subdivided by the nine major world regions in the world. Data are based on [30,33,40–47].

	Trading among sub-regions		Demand covered by storage			Battery share of storage discharge		
Scenario	Area	Integrated	Region	Area	Integrated	Region	Area	Integrated
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Northeast Asia	11	10	20	16	12	67	68	79
Southeast Asia	6	3	20	17	11	75	80	88
India/SAARC	14	23	24	21	19	73	75	71
Eurasia	20	13	4	6	5	9	4	1
Europe	14	15	17	11	8	33	45	55
MENA	12	10	18	11	11	53	63	23
Sub-Saharan Africa	9	10	15	13	9	64	68	65
North America	23	24	21	13	6	63	72	96
South America	11	8	13	8	7	90	99	91
World	15	14	19	14	10	63	69	75

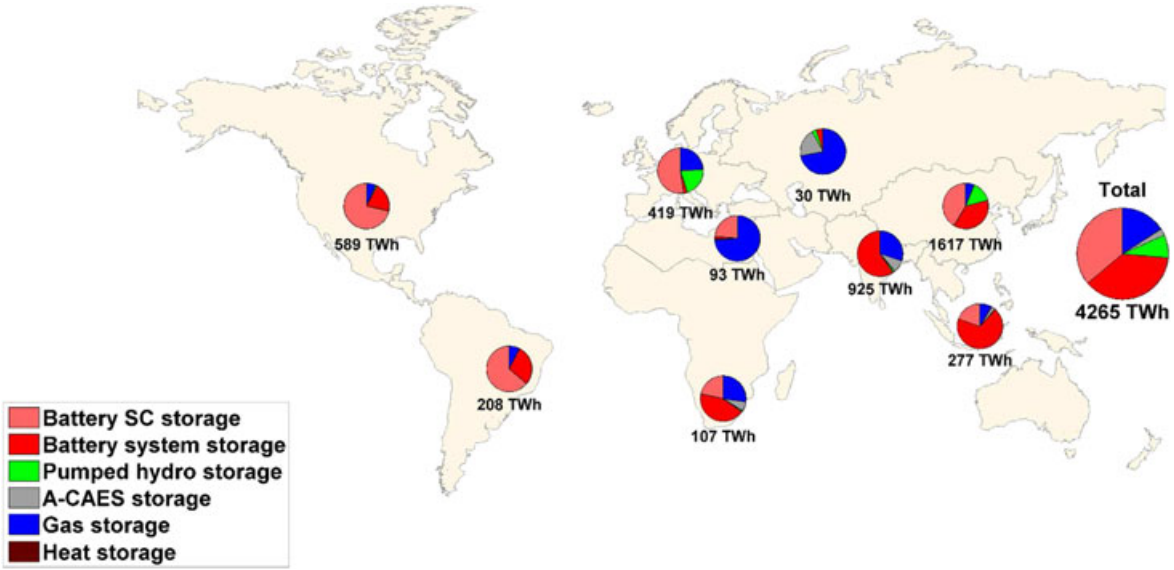

Figure 8. Storage discharge for the integrated scenario in a global overview structured in the nine major world regions: Northeast Asia, Southeast Asia, India/SAARC, Eurasia, Europe, MENA, Sub-Saharan Africa, North America and South America. Data are taken from [30,33,40–47]. A-CAES, adiabatic compressed air energy storage; SC, self-consumption.

100% RE system, but for all energy sectors, and find a demand of 32.7 TWp, which is close to the extrapolation of the 27.4 TWp found with the LUT Energy system model. Findings for the year 2050, in which the energy system should be close to a net zero greenhouse gas emission system to reach the COP21 targets [70], indicated significantly more progressive expectations for other energy transition scenarios, such as 6.7–9.3 TWp for Greenpeace Energy [R]evolution, 11.0 TWp for the PV Power Systems Programme of the IEA, 20.0 TWp for the Shell Oceans scenario and 32.7 TWp derived by Jacobson and Delucchi. Summing up, Jacobson and Delucchi find similar capacities for their 100% RE system; however, they derive it not on an hourly basis and therefore do not have battery storage in their energy system. This does not seem realistic given the fast cost decline of batteries, but it is a consequence of their chosen equilibrium approach. For all other energy transition scenarios for the 2040 assumptions, only the Greenpeace Energy [R]evolution scenario finds comparable PV capacities. For the year 2050, comparable findings are derived by Greenpeace, IEA-PVPS and Shell Oceans.

The share of solar PV in the electricity sector is assumed by Greenpeace to be at around 20% and by WWF at 29%, which are both closest to the 41% found with the LUT Energy system model, but both are significantly lower than the LUT Energy system model results. Taking into account all solar energy technologies, then the picture is found to be different, because several energy transition

scenarios find substantial shares for the year 2050, such as 22% and 29% by Greenpeace, 30% by WWF, 17–24% by IIASA GEA, 28% by the WBGU and 40% by Jacobson and Delucchi. Noteworthy, the IPCC scenarios are all below 20%, and two are between 1% and 7%, clearly indicating the outdated cost assumptions.

Latest results on energy system transition modelling for the case of Saudi Arabia [79] indicates that the solar PV share of energy supply will substantially grow beyond the year 2030, because the solar PV share grew up to 80% for Saudi Arabia for the year 2050 as a consequence of ongoing learning curve progress of solar PV and batteries.

The results of the LUT Energy system model for 2030 assumptions cannot be compared with 2100 results of other scenarios, because the ongoing cost decline of solar PV and battery technologies will further increase the PV share. As a consequence, the 41% energy supply share already found can be expected as the lower limit of the long-term solar PV share. Comparable shares are expected by two IPCC models, indicating again their outdated cost assumptions, which are not so relevant in the long-term. Jacobson and Delucchi find, at 40%, a very comparable PV share, as well as the long-term share of the Shell Mountains scenario. Outstanding is the expectation of the WBGU energy transition scenario, with a 67% solar energy supply share in the year 2100.

The biophysical limits of the global energy system have to be taken strictly into account because humankind is starting to transform planetary systems which led to the beginning of a new geological age, the Anthropocene [80]. Bardi [81] recently added a biophysical interpretation emphasizing the coming age of solar energy, which is fully supported by the findings of this paper. The substantial capacities of solar PV required for the 100% RE scenario presented in this research can be checked against the area needed to establish that energy harvesting infrastructure. The key results of this study indicate PV capacities of 12.0, 27.4 and 42.3 TWp. The prosumer PV share is 3.7 TWp, which is allocated on rooftops. As such, they are zero impact areas [82], hence do not require additional area. The remaining capacities for land demand are 8.3, 23.7 and 38.6 TWp. The specific capacity density is derived in the LUT Energy system model to be 75 MW/km^2 [30], hence an area of 110 670, 316 000 and 514 670 km^2 is needed, representing 0.07%, 0.21% and 0.35% of the global land mass. This very small fraction of global land mass demand seems to be acceptable taking into account that the current energy system is more than 50% responsible for the ecological footprint of humankind, equal to 1.5 times the capacity of planet Earth [1].

Some of the results of the LUT Energy system modelling are noteworthy for further discussion. The LUT Energy system model is the only one which calculates 100% RE scenarios on a full hourly resolution, on a global level, and with a high geographical resolution of 145 subregions (which are composed of resource data for solar and wind at a 0.45° × 0.45° resolution). None of the global energy transition scenarios show this high level of temporal and spatial resolution. This leads to several implications, such as no quantifiable storage capacities and a weak description of the complementarity of solar PV, wind energy, hydro dams and biomass plants. In addition, the most important geographic balancing function of power grids can be not considered in the energy transition scenarios, at all. As well, the cost reducing and efficiency increasing functions of a power-based sector coupling are also beyond the methodological features of those models, because they cannot model the flexibility on an hourly scale.

The highly competitive levelised cost results for the LUT Energy system model scenarios, at 65 €/MWh (region-wide), 58 €/MWh (area-wide) and 49 €/MWh (integrated), needs to be further highlighted, because this means that 100% RE systems are substantially lower in cost than the cost assumptions for fossil carbon capture and storage (CCS) and new nuclear plants in Europe, which are expected to be around 112 €/MWh for new nuclear (assumed for 2023 in the UK and Czech Republic), 112 €/MWh for gas CCS (assumed for 2019 in the UK) and 126 €/MWh for coal CCS (assumed for 2019 in the UK) [83]. However, a report commissioned by the European Commission (DG Energy) [84] concludes that CCS technology is not likely to be commercially available before the year 2030. A variation of the WACC does not substantially alter the results, because WACC of 5% and 9% leads to −15% and +17% energy system cost, respectively, in comparison with the set 7%. Because nuclear energy and fossil CCS are also mainly based on capital expenditures, the relative cost difference is rather small. However, the risk profile of nuclear energy and fossil CCS is much higher than renewable energy, which should result in a higher WACC level of nuclear energy and fossil CCS compared with renewable energy technologies. Depending on the interest rate and the debt to equity ratio, the return on equity can be up to 18% for WACC of 9%.

The LUT Energy system model is currently further developed to reach a full energy sector description including the sectors heating, mobility and industrial demand. Furthermore, the first energy transition simulations can be done on a single sub-regional basis [79], and the coverage of the full global energy system is in preparation.

There have been estimates of the long-term solar PV demand carried out recently leading of slightly more than 90 TWp [85,86] based on a 40% energy supply share of PV. This is in substantial deviation by a factor of two to the 42.3 TWp found in this paper. The preliminary hypothesis for this deviation is that the enormous efficiency improvement of an energy system based on renewable electricity is underestimated in the recent estimates, because mid-2010s TPED per capita of Europe is extrapolated for a world population at the same wealth level. However, the current energy system is very inefficient, which can be illustrated best by a low average efficiency of the installed base of thermal power plants of only 35% [9], the low efficiency of current combustion cars of less than 20% or the limited efficiency of heating systems to

slightly less than 100%—compared with close to 100% utilization of renewable electricity plants, 70–80% efficient electric vehicles or 300–400% efficient electric heat pumps. The shift to power megatrend may have the potential to increase the total energy system efficiency dramatically. This hypothesis can be investigated further by energy system transition scenarios taking into account very high shares of renewable electricity for the total energy supply.

6. CONCLUSIONS

The research question of this paper is about the mid-term to long-term solar PV demand in a world based on sustainable energy resources.

Global installed solar PV capacity hit 237 GWp by end of 2015, and this is a small fraction of the capacity in the decades to come. The net-zero greenhouse gas emission target of the COP21 agreement in Paris [70] may lead to a global energy system based on very high shares of RE. A 100% RE system modelling with the high temporal and spatial resolution of the LUT Energy system model leads to an energy supply share of solar PV of slightly more than 40% and solar PV capacities of about 27 and 42 TWp from the mid to the end of the 21st century. This outcome is lower than recent long-term PV demand estimates of about 90 TWp [85,86] based on a comparable PV supply share despite identical assumed energy service demands, because the efficiency gains of the shift to power megatrend may be higher than previously anticipated (e.g. heat pumps and electric vehicles are 3–4 times more efficient and power-to-gas/liquids may be comparably efficient with biofuels and the conventional fossil fuel value chain [87,88]) and system benefits from sector integration. The most progressive global benchmarking scenarios can be confirmed by the key findings of this research, however, now based on a more sophisticated fundamental methodology. Furthermore, the clear result of 100% RE system analysis based on LUT Energy system modelling is the low cost of 49–65 €/MWh for the given scenario assumptions, which is substantially more competitive than low carbon fossil-CCS and nuclear alternatives.

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APPENDIX A

Table A1. Financial assumptions for energy system components [30].

Technology	Capex [€/kW]	Opex fix [€/kW]	Opex var [€/kWh]	Lifetime [a]
PV optimally tilted	550	8	0	35
PV single-axis tracking	620	9	0	35
PV rooftop	813	12	0	35
Wind onshore	1000	20	0	25
CSP (solar field)	528	11	0	25
Hydro run-of-river	2560	115.2	0.005	60
Hydro dam	1650	66	0.003	60
Geothermal energy	4860	87	0	30
Water electrolysis	380	13	0.0012	30
Methanation	234	5	0.0015	30
CO_2 scrubbing	356	14	0.0013	30
CCGT	775	19.4	0.001	30
OCGT	475	14.25	0.001	30
Steam turbine	600	12	0	30
Hot heat burner	100	2	0	30
Heating rod	20	0.4	0.001	30
Biomass CHP	2500	175	0.001	30
Biogas CHP	370	14.8	0.001	30
Waste incinerator	5240	235.8	0.007	20
Biogas digester	680	27.2	0	20
Biogas upgrade	250	20	0	20
	Capex [€/kWh]	Opex fix [€/kWh]	Opex var [€/kWh]	Lifetime [a]
Battery	150	10	0.0002	10/20
PHS	70	11	0.0002	50
A-CAES	31	0.4	0.0012	40
TES	24	2	0	20
Gas storage	0.05	0.001	0	50
	Capex [€/(kW_{NTC}*km)]	Opex fix [€/(kW_{NTC}*km)]	Opex var [€/kWh_{NTC}]	Lifetime [a]
HVDC line on ground	0.612	0.0075	0	50
HVDC line submarine	0.992	0.0010	0	50
	Capex [€/kW_{NTC}]	Opex fix [€/kW_{NTC}]	Opex var [€/kWh_{NTC}]	Lifetime [a]
HVDC converter pair	180	1.8	0	50
	Capex [€/(m^3 a)]	Opex fix [€/(m^3 a)]	Opex var [€/m^3]	Lifetime [a]
Water desalination	2.23	0.09	0	30
	Capex [€/(m^3 h km)]	Opex fix [€/(m^3 h km a)]	Opex var [€/(m^3 h km)]	Lifetime [a]
Horizontal pumping and pipes	19.3	0.39	0	30
Vertical pumping and pipes	15.5	0.31	0	30

All technical and financial assumptions are for the year 2030 in currency values of the year 2015. A-CAES, adiabatic compressed air energy storage; Capex, capital expenditures; CCGT, combined cycle gas turbines; CHP, combined heat and power; CSP, concentrating solar thermal power; HVDC, high voltage direct current; OCGT, open cycle gas turbines; Opex, operational expenditures; PHS, pumped hydro storage; PV, photovoltaic; TES, thermal energy storage.

Table A2. Efficiencies and energy to power ratio of storage technologies for the 2030 reference year [30].

Technology	Efficiency [%]	Energy/power ratio [h]	Self-discharge [%/h]
Battery	90	6	0
PHS	85	8	0
A-CAES	70	100	0.001
TES	90	8	0.002
Gas storage	100	80*24	0

A-CAES, adiabatic compressed air energy storage; PHS, pumped hydro storage; TES, thermal energy storage.

Table A3. Efficiency assumptions for energy system components for the 2030 reference year [30].

	η_{el} [%]	η_{th} [%]
CSP (solar field)		51
Steam turbine	42	
Hot heat burner		95
Heating rod		99
Water electrolysis		84
Methanation		77
CO_2 scrubbing		78
CCGT	58	
OCGT	43	
Geothermal	24	
Biomass CHP	40	45
Biogas CHP	42	43
Waste incinerator	34	
Biogas upgrade		98

CHP, combined heat and power; CSP, concentrating solar thermal power; CCGT, combined cycle gas turbines; OCGT, open cycle gas turbines.

Table A4. Efficiency assumptions for HVDC transmission for the 2030 reference year [30].

	Power losses
HVDC line	1.6%/1000 km
HVDC converter pair	1.4%

HVDC, high voltage direct current.