Solar photovoltaic capacity demand for a sustainable transport sector to fulfil the Paris Agreement by 2050

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ABSTRACT

The Paris Agreement sets a clear target for net zero greenhouse gas (GHG) emissions by the mid-21st century. This implies that the Transport sector has to reach zero GHG emissions mainly through direct and indirect electrification in the form of synthetic fuels, such as hydrogen and Fischer-Tropsch (FT) fuels. The results of this research document that this very ambitious target is possible. This research analyses the global solar photovoltaics (PV) demand for achieving the Paris targets in the Transport sector by the year 2050. The methodology is comprised of the derivation of the transportation demand converted into final energy demand for direct electrification, hydrogen, methane and FT-fuels production. The power-to-gas (H_2, CH_4) and power-to-liquids (FT-fuels) value chains are applied for the total electricity demand, which will be mostly fulfilled by PV, taking into account previous results concerning the renewable electricity share of the energy transition in the Power sector for the world structured in 145 regions and results aggregated to nine major regions. The results show a continuous demand increase for all transportation modes till 2050. The total global PV capacity demand by 2050 for the Transport sector is estimated to be about 19.1 TWp, thereof 35%, 25%, 7% and 33% for direct electrification, hydrogen, synthetic natural gas, and FT-fuels, respectively. PV will be the key enabler of a full defossilisation of the Transport sector with a demand comparable to the Power sector but a slightly later growth dynamic, leading to a combined annual PV capacity demand of about 1.8 TWp around 2050.

Keywords

Photovoltaic, Transport Sector, Energy System, 100% Renewable Energy, Energy Transition, Power-to-Gas, Power-to-Liquids, Electrification

1. Motivation

The global Transport sector represents about 18.5% (31,310 TWh$_{th}$ in 2015) of the total global primary energy demand [1] (Fig. 1) and contributes about 23% (7.44 Gt$_{CO2}$/a in 2015) [1] and 15% to global greenhouse gas (GHG) emissions of the energy system and in total, respectively. This needs to be reduced to zero by the mid of the 21st century in order to satisfy the Paris Agreement [2]. Net zero GHG emissions, with remaining positive emissions, will not be an

option for the Transport sector, since negative emission technologies (NETs) [3,4] are very cost intensive and only justified for almost impossible reductions in the agricultural sector and other technically unavoidable GHG emissions. This implies zero GHG emission fuels for the Transport sector, which can be achieved best by direct electrification, in particular for road and rail transport. For two- and three-wheelers (2W/3W), buses, light duty vehicles (LDV) and medium duty vehicles (MDV), electrification may be easier than for heavy duty vehicles (HDV). Whereas, direct electrification is almost impossible for most segments of marine and aviation due to the long distances and very heavy ships and planes. Nevertheless, some direct electrification may be achieved for short distance shipping (up to 100 km) [5,6] and, in the future, flights (up to 1.5-3 hours) [7,8]. The required high energy density fuels, mainly for ships and planes and partly for HDVs, can be provided by electricity-based synthetic fuels, such as hydrogen (H_2), synthetic natural gas (CH_4) and Fischer-Tropsch (FT) fuels [9]. The used electricity needs to be fully based on renewable sources to match the targets of the Paris Agreement as well as overall sustainability [10] and economic constraints. It was shown in a previous study that a full defossilisation of the Power sector is possible by 2050 based on 100% renewable energy (RE) [11,12,13]. The 100% RE power system is expected to be lower in cost than the current electricity system and other alternatives [11], which constitutes the hypothesis that a fully RE-based Transport sector would also be a least cost solution under the given constraints. The technical feasibility and the economic viability of 100% RE systems are discussed in a fast growing number of research pieces [14]. Biofuels alone cannot solve the challenge of the Transport sector due to limited resource availability, sustainability issues and cost constraints [15,16,17]. Some unsustainable, currently used biofuels may be substituted by less constrained and more suitable options such as jatropha-based fuels [18].
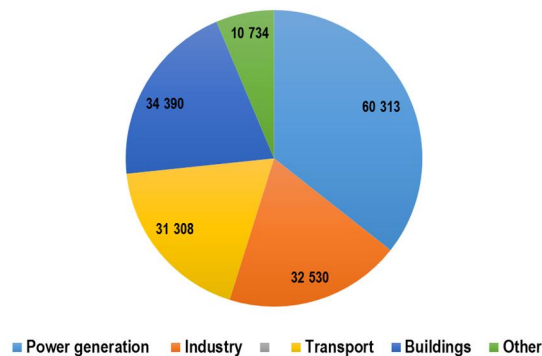

Figure 1: Breakdown of global final energy demand of about 169,300 TWh$_{el,th}$ in 2015. Data are taken from [1].

This paper presents for the first time the contribution of solar photovoltaics (PV) to the global Transport sector as it transitions to a 100% RE-based system by 2050. Detailed results of the Power sector transition towards 100% RE for 145 regions are aggregated to nine major world regions and applied to the Transport sector. The results demonstrate that solar PV may emerge as the major source of energy for a net zero emissions Transport sector by 2050 globally.

2. Methodology

2.1 Overview on general approach

Transportation demand is derived for the main segments road, rail, marine and aviation for passenger and freight transportation [19]. The road segment is sub-structured into passenger LDV, passenger 2W/3W, passenger bus, freight MDV, and freight HDV. The other transportation modes are comprised of demand for freight and passengers. The demand is estimated in passenger kilometers (p-km) for passenger transportation and in (metric) ton kilometers (t-km) for freight transportation. The data for transportation demand, but also fuel shares and specific energy demand are based on key references, such as International Council on Clean Transportation (ICCT) [20], International Civil Aviation Organization (ICAO) [21], International Maritime Organization (IMO) [22], European Commission (EC) [23], International Energy Agency (IEA) [24,25], Greenpeace [26] and others, all summarised by Khalili et al. [19].

The transportation demand is converted into energy demand by assuming an energy transition from current fuels to fully sustainable fuels by 2050, whereas the following principle fuel types are taken into account and visualised in Figure 2:
- Road: electricity, hydrogen, liquid fuels
- Rail: electricity, liquid fuels
- Marine: electricity, hydrogen, methane, liquid fuels
- Aviation: electricity, hydrogen, liquid fuels

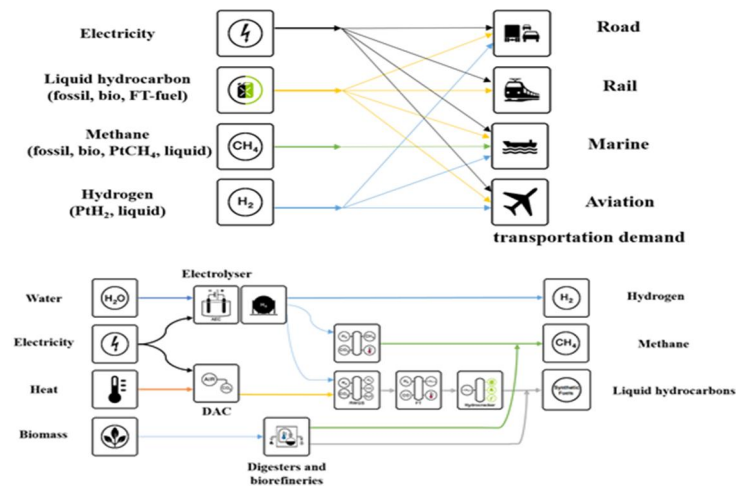**Figure 2:** Transportation modes and considered fuels (top) and value chain elements for sustainable fuels (bottom). Figure is taken from [13].

The fuel shares of the transportation modes in the road segment are based directly or indirectly on levelised cost of mobility (LCOM) considerations for newly sold vehicles, which change the stock of vehicles according to the lifetime composition of the existing stock. Vehicle stock and

overall demand data are then linked to specific energy demand values to calculate demand of fuels and electricity for the Transport sector. The specific energy demand values for converting transportation demand into energy demand are taken from various sources [19]. The electricity demand to produce hydrogen and FT-fuels (diesel, petrol, kerosene) is derived by applying respective value chains [9], and taking CO_2 direct air capture (DAC) [27,28] into account to achieve the required level of sustainability. The CO_2 could also originate from a carbon point source, which is either sustainable due to bio-CO_2 (pulp & paper mills [29]) or unavoidable due to lack of better options (limestone fraction of cement mills [30] or municipal solid waste incinerators). CO_2 DAC is also taken into account in this research due to the limited amount of sustainable and unavoidable carbon point sources [27]. The RE-based electricity to cover the transportation demand is assumed to be covered by the same mix of RE as derived by Breyer et al. [11] for the Power sector of the nine major regions. This allows linking the average PV yield of the respective major region to the transportation demand, assuming a comparable demand distribution for the Power and Transport sectors.

The LUT Energy System Transition modelling tool [11,12,13,31] simulates an energy system under given conditions. The computer simulation for the Power sector is applied for 5-year time steps for the period from 2015 to 2050. For every time step the model defines a cost optimal energy system structure and operation mode for the given set of constraints: power demand, available generation and storage technologies, financial and technical assumptions, and limits on installed capacity for all applied technologies. The model is based on a linear optimisation and performed with hourly resolution for an entire year. This provides a high precision and reliability of results. Costs of the system are calculated as the sum of the annual capital and operational expenditures (including ramping costs) for all available technologies. The LUT Energy System Transition model for the Power sector is described in detail elsewhere [11,12,13,31].

2.2 Resource potential for sustainable Transport sector

In the energy transition of the Transport sector, the final energy demand of the sector by 2050 will be met by a fully sustainable energy system.. Due to the sustainability limits [15,16,17] it is assumed that the contribution of biofuels does not grow as relative share, but that a shift may happen to more sustainable biofuels from degraded land, such as jatropha [18]. The remaining final energy demand can be covered by direct and indirect electrification, which is assumed to be a fully renewable one by 2050 [11,12,13]. Solar PV and wind energy are the only RE sources, which are not effectively limited and low cost [11,12,13]. Other renewable electricity sources, such as hydropower, biomass, or geothermal, are either limited or not low cost. Therefore, it is assumed for this research that all electricity demand for the Transport sector has to be provided by solar PV and wind energy.

2.3 Transportation demand of a fully sustainable Transport sector

Transportation demand is summarised in Table 1 and the assumed RE shares for the hydrogen and methane supply and liquid fuels distribution are summarised in Table 2. The data shows a

continuous demand increase of all transportation modes for passenger and freight transportation by about 200% from 2015 to 2050. The total global demand is presented, based on an individual demand analysis for all countries in the world [19]. The expected scenario for the development of the fuels in the five major road segments, and for rail, marine and aviation is visualised in Figures 3 and 4, respectively. The applied efficiencies for Power-to-Gas (PtG) for H_2 is 84%, for CH_4 57% and for FT-fuels 53% [9]. The scenario for the fuels and powertrains in the road segments leads to a comparably high battery electric vehicles (BEV) and low fuel cell electric vehicles (FCEV) share, which is also a consequence of the relative efficiencies of the entire energy conversion chain from primary electricity generation to the wheels of vehicles, which leads to efficiencies of about 40% for FCEV and 70-80% for BEVs. Finally, the LCOM are the decisive driver for the shares of fuels and powertrains, as discussed in more detail in Khalili et al. [19].

Table 1: Summary of transportation demand for the various transportation segments. Data are taken from [19].

		2015	2020	2025	2030	2035	2040	2045	2050
Road Passenger	[m p-km]	46 103 903	54 712 512	62 274 258	71 099 767	80 545 530	91 898 505	105 296 525	120 738 540
Road Freight	[m t-km]	12 70730	14 831 669	16 783 028	19 066 497	21 665 434	24 856 152	28 384 647	32 156 417
Rail Passenger	[m p-km]	3 820 817	4 572 627	5 170 556	5 791 790	6 280 429	6 854 162	7 503 759	8 192 956
Rail Freight	[m t-km]	11 140 510	12 302 151	13 332 887	14 519 992	15 897 869	17 591 259	19 566 434	21 857 097
Marine Passenger	[m p-km]	125 734	151 496	184 611	226 494	278 149	339 878	411 257	491 297
Marine Freight	[m t-km]	83 961 402	98 979 938	116 550 168	137 401 513	162 471 865	192 967 184	230 438 154	276 878 767
Aviation Passenger	[m p-km]	5 629 260	6 865 655	8 434 501	10 664 704	13 131 094	17 024 295	21 519 565	26 362 577
Aviation Freight	[m t-km]	197 554	264 371	353 788	473 448	633 580	862 956	1 156 873	1 514 400
Total	[m t-km]	108 006 196	126 378 128	147 019 871	171 461 449	200 668 748	236 277 551	279 546 107	332 406 681
Total	[m p-km]	55 679 714	66 302 289	76 063 926	87 782 756	100 235 202	116 116 840	134 731 105	155 785 371

Table 2: Summary of RE share for electricity, electricity share for hydrogen and methane, and RE share for liquid fuels. Numbers below 100% electricity share of hydrogen/ methane, RE share of liquid fuels and RE share of electricity indicate the remaining for fossil fuels for hydrogen/ methane and liquid fuels and fossil-nuclear for electricity, respectively. Data are taken from [19].

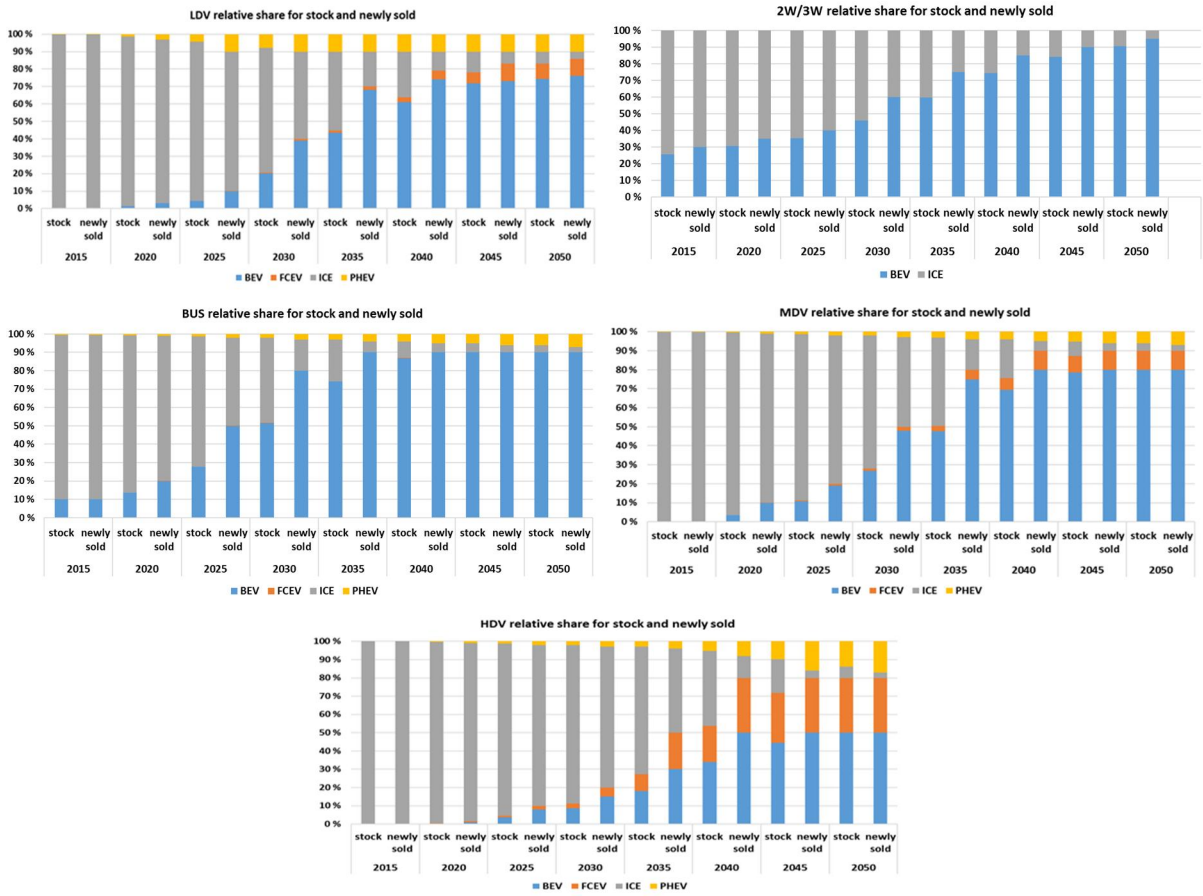|	2015	2020	2025	2030	2035	2040	2045	2050
RE share electricity	22.3%	40.2%	73.7%	89.4%	96.1%	98.0%	99.0%	99.7%
electricity share hydrogen	0%	10%	25%	50%	65%	85%	95%	100%
electricity share methane	0%	0%	0%	3%	18%	43%	77%	100%
RE share liquid fuels	3%	4%	4%	7%	22%	47%	77%	100%
thereof biofuels	3%	4%	4%	4%	4%	4%	4%	4%
thereof FT-fuels	0%	0%	0%	3%	18%	43%	73%	96%

Figure 3: Development of fuel shares in five road segments: LDV (top left), 2W/3W (top right), Bus (center left), MEV (center right) and HDV (bottom). Data are taken from [19].
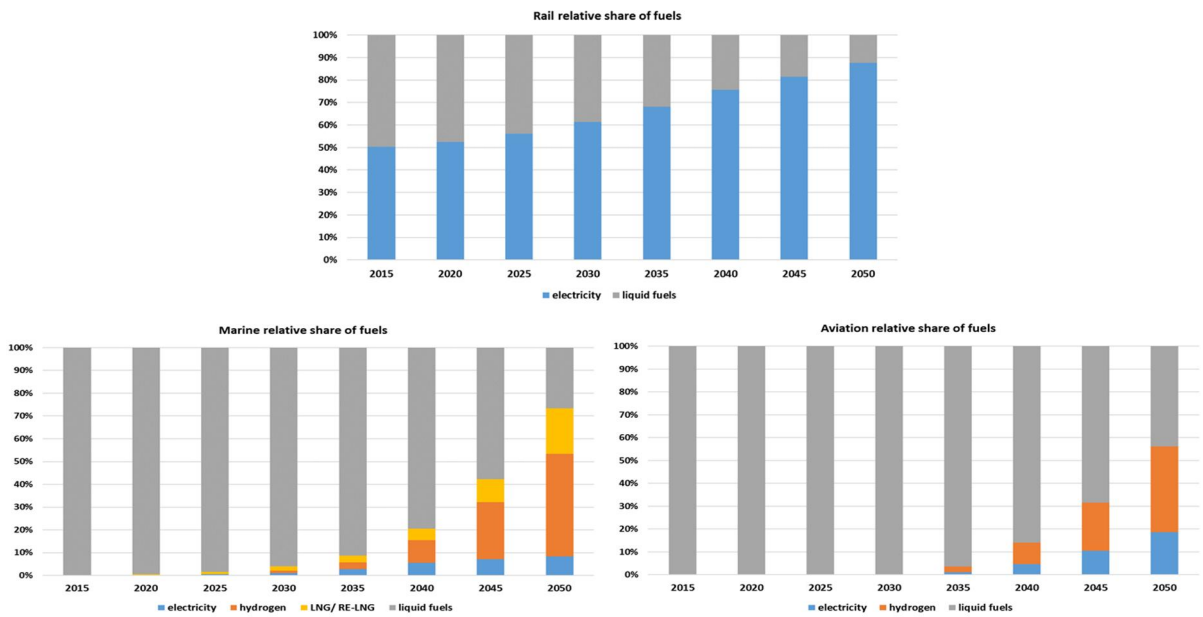

Figure 4: Development of fuel shares for rail (top), marine (bottom left) and aviation (bottom right). Data are taken from [19].

2.4 Energy demand of a fully sustainable Transport sector

The anticipated strong direct electrification in the road and rail segments, continued higher demand of liquid fuels, and more energy intensive PtG (H_2, CH_4) fuels for the marine and aviation segments lead to a drastic relative final energy demand shift towards marine and aviation. However, the substantial efficiency gain of direct electrification, in particular in the road segments, leads to a stabilisation of the final energy demand of the Transport sector at around 32,500 TWh, depicted in Figure 5, despite strong transportation demand increase.

A substantial efficiency gain can be realised for the road segments, since the overall increase in transportation demand from 46,100 to 120,740 billion p-km and 12,710 to 32,160 billion t-km for passenger and freight transportation (2015 to 2050) can be realised by a decline in final energy demand of 15,730 to 8,960 TWh and 8,240 and 5,780 TWh for passenger and freight transport. The current electrification of the road segments can be observed in waves, with the highest relative share achieved for 2W/3W, fast growing shares for buses and starting for LDV, followed by MDV and HDV [25]. These waves can be observed best in Asia, in particular in China.
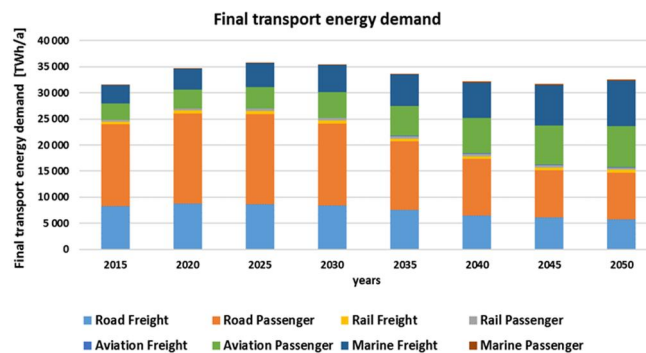

Figure 5: Development of final energy demand for the Transport sector.

The composition of the final energy demand in 2050 is direct electricity (35%), hydrogen (25%), methane (7%) and liquid fuels (33%). The massive efficiency gain in the Transport sector is documented by the fact that only 35% direct electrification share in the final energy demand is equivalent to 76% and 19% of all Transportation demand for passengers and freight, respectively. This massive shift in final energy demand for fuels and the respective transportation efficiency can be explained by a huge increase in the energy efficiency for directly electrified transportation. For example, this is demonstrated by road passenger LDV, for which 0.782 kWh_{th}/km are needed for internal combustion engines (ICE) in 2015, but 0.096 kWh_{el}/km for BEVs in 2050 [19]. The external electricity demand of BEVs may be further reduced by vehicle-integrated PV [32,61], that has been demonstrated by Sono Motors to extend the range of a BEV by up to 30 km per day [33]. Another example is for the expected tremendous efficiency gain in direct electric aviation, with an efficiency gain from 0.545 kWh_{th}/p-km (2015, kerosene) to 0.141 kWh/p-km (2050, electricity) [19].

The derived electricity demand for direct and indirect electrification is dominated by indirect demand for hydrogen, methane and FT-fuels as depicted in Figure 6. These findings are confirmed by a recent publication of García-Olivares et al. [34]. The very high relative indirect electrification demand is driven by the aforementioned high energy efficiency of direct electric transportation, but also by the conversion efficiency of electricity to hydrogen (84%), methane (57%) and FT-fuels (53%). The total electricity demand for a sustainable Transport sector is comprised in 2050 of electricity (26%), hydrogen (22%), methane (8%) and FT-fuels (44%). The conversion efficiency for indirect electrification reduces the direct electrification share of 35% of the final energy demand to 26% of the total electricity demand.
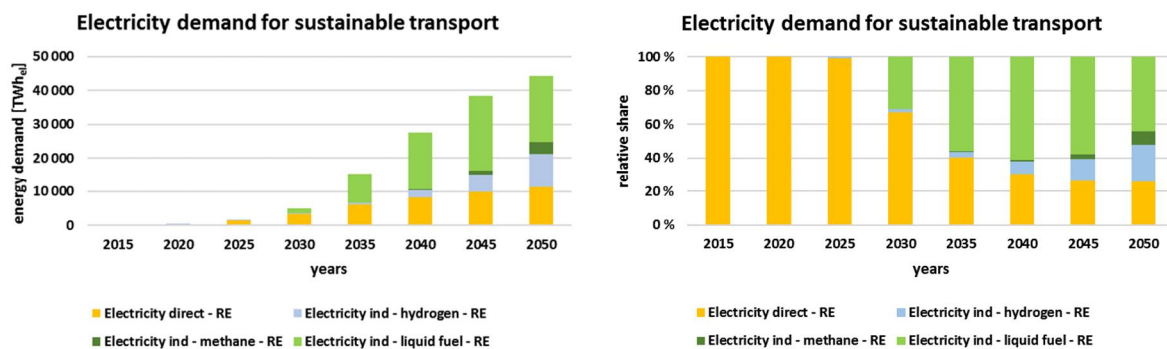

Figure 6: Development of electricity demand for the Transport sector in absolute (left) and relative (right) distribution to the final energy fuels.

The growth phases for electricity demand in the Transport sector are mainly three:
- 2015 – 2030: almost only direct electrification, in particular for the various road segments
- 2030 – 2050: electricity demand for FT-fuels is strongly growing
- 2040 – 2050: electricity demand for hydrogen and methane is growing

3. Results

The underlined transition of the Transport sector is based on Khalili et al. [19] and of the Power sector on Breyer et al. [11], Ram et al. [12] and Bogdanov et al. [13], which leads the Transport sector also to very high levels of sustainability, since a 100% renewable electricity supply forms the energetic basis (along with 4% biofuels) of the Transport sector throughout the energy transition till 2050.

The total global PV capacity demand by 2050 for the Transport sector is derived to be about 19.1 TWp. This result is based on the following assumptions:
- The electricity demand by 2050 has to be provided by renewable electricity.

- The results of Breyer et al. [11] are taken as a basis for deriving the results for the Transport sector.
- Since limited renewable resources, such as bioenergy and hydropower, are already used in the Power sector, only solar PV and wind energy are assumed to cover the electricity demand of the Transport sector.
- The relative solar PV to wind energy share grows from about 62% (min-max of the nine major regions is 24% and 91% respectively) in 2035 to about 89% (min-max of the nine major regions is 37% and 96% respectively) in 2050 according to Breyer et al. [11], mainly due to strong demand growth in Sun Belt regions of the world, but also due to increasing relative competitiveness of PV-battery based system solutions.
- The global averaged and generation weighted yield of utility-scale solar PV systems is 1883 kWh/kWp (min-max of the nine major regions is 1518 kWh/kWp and 2226 kWh/kWp respectively) in 2050, assuming no contribution of PV prosumers for transport [35], which would be part of a later model upgrade. Single-axis tracking PV systems contribute about 87% to the generation weighted yield according to Breyer et al. [11] described in more detail in Afanasyeva et al. [36].
- A total loss from generation to demand of about 14% is taken into account, which is comprised of about 8% curtailment, about 4% for storage losses in the energy system and about 2% for respective grid losses, all based on the results of Breyer et al. [11] and described in more detail for the grid losses in Sadovskaia et al. [37].
- 4% of the liquid fuel demand is covered by biofuels.

The electricity demand plotted in Figure 6 is transformed to the electricity demand, including all assumptions and losses mentioned above, and visualised in Figure 7. The figure clearly shows that from 2030 onwards the Transport sector will generate substantial PV demand, and from 2040 onwards the indirect electrification demand starts to become larger than the direct electrification demand from the Transport sector. This leads to a total of about 32,500 TWh$_{el}$ of solar PV generation demand for the Transport sector in 2050. The total energy demand of the Transport sector is covered in 2050 by about 78% solar PV (min-max of the nine major regions is 36% and 94% respectively). This share is higher than the found 69% of total Power sector supply of solar PV [11,12,13], since hydropower and bioenergy are limited due to resource, sustainability and economic reasons. It is also assumed that the available resources are already used for the Power sector.
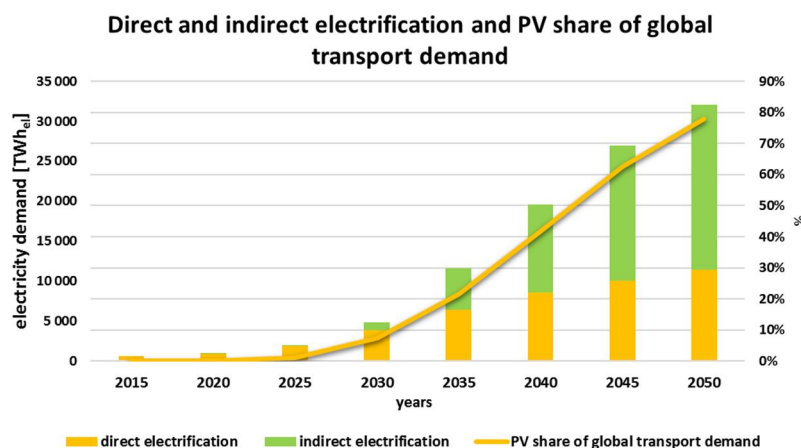
Figure 7: Development of solar PV generation for the Transport sector and relative PV share of total Transport sector energy supply.

Key results for the solar PV demand for the Transport sector in 2050 are summarised in Table 3. The distribution of the total global PV capacity demand of 19.1 TWp of the Transport sector by 2050 to the nine major regions is visualised in Figure 8. The two dominating regions for the PV capacity demand are Northeast Asia, with China, and South Asian Association for Regional Cooperation (SAARC), with India, with around a quarter each of the total global PV capacity demand.

Table 3: Key results for the energy transition in the Transport sector and resulting demand for solar PV in 2050.

	share global transportation demand	electricity demand				PV share in Transport sector	Yield PV utility-scale	PV capacity demand
		direct	indirect	losses	total			
	[%]	[TWh$_{el}$]	[TWh$_{el}$]	[TWh$_{el}$]	[TWh$_{el}$]	[%]	[kWh/kWp]	[TWp]
[Europe	13.2%	1 237	4 739	1 051	7 026	59.8%	1581	2 329
Eurasia	3.6%	409	1 191	172	1 772	36.7%	1518	375
MENA	5.9%	573	2 094	438	3 105	81.7%	2189	1 034
SSA	5.3%	338	2 140	445	2 923	91.8%	2226	1 083
SAARC	20.9%	2 739	6 336	1 512	10 586	93.9%	1999	4 463
Northeast Asia	24.1%	3 388	6 906	1 595	11 889	79.8%	1736	4 906
Southeast Asia	6.6%	697	2 244	536	3 476	95.5%	1818	1 636
North America	14.7%	1 402	5 275	1 242	7 919	62.1%	1993	2 160
South America	5.8%	638	1 947	273	2 858	88.2%	2059	1 092
Global	100.0%	11 420	32 871	7 264	51 556	78.0%	1883	19 078

Total global: 19078 TWp
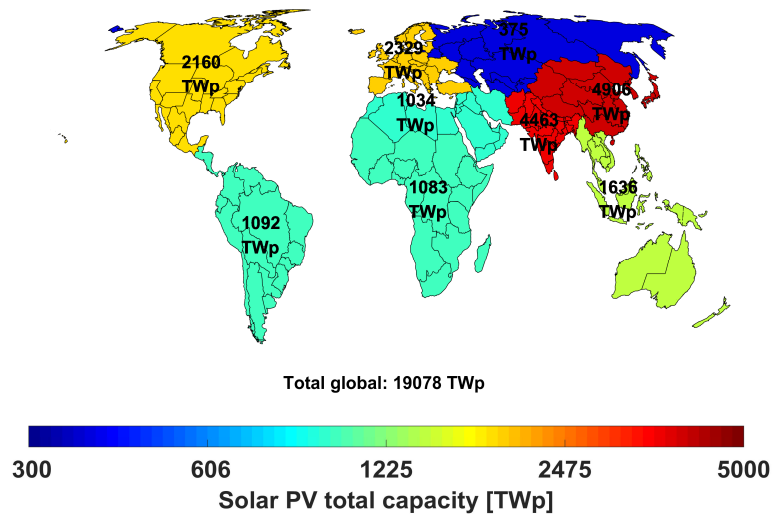
Solar PV total capacity [TWp]

Figure 8: Distribution of total global PV capacity demand for the Transport sector by 2050 to the nine major regions.

FT-fuels can be produced in diesel or kerosene modes, which allow finally 80% of the output to be used in the Transport sector. The naphtha share is around 15% and 25% in the diesel and kerosene modes, respectively, leading to about a 20% naphtha share in the final production mix. Naphtha is a valuable feedstock for the chemical industry. An additional 2.4 TWp PV capacity is allocated to the FT by-product naphtha, which may be equivalent to about 14% of the feedstock demand of the chemical industry in 2050, based on the estimated global feedstock demand of the chemical industry of about 19,200 TWh$_{th}$ in 2050 [38,39].

4. Discussion

This research highlights the very high relevance of solar PV for the defossilisation of the Transport sector for direct and in particular indirect electrification. It has to be highlighted that the results confirm that all GHG emissions of the Transport sector can be reduced to zero by 2050 following the outlined projection. Breyer et al. [11] estimate a cumulative installed PV capacity demand in the Power sector of 21.9 TWp in 2050, and this research adds an additional demand of 19.1 TWp for the Transport sector. FT-fuel production also leads to feedstock for the defossilisation of the chemical industry of about 14% of total demand, equivalent to a further 2.4 TWp.

The methodology has been improved for this research to estimate the global solar PV capacity demand by applying earlier results [11,12,13] individually for the nine major regions, in comparison to a very first estimate based on global average PV metrics [40]. The deviation is 0.016% in the electricity demand in 2050 and 0.013% in the cumulative installed PV capacity demand for the Transport sector, due to more detailed calculation individually for all nine major regions compared to the global average. The improved quality in this research is therefore not only the higher accuracy but also the individual results per major region. Future research should

derive the PV capacity demand for the Transport sector on full hourly resolution for all 145 regions so that the remaining uncertainty can be overcome.

The total cumulative PV capacity demand is derived assuming CO_2 DAC [27], based on earlier publications [9,41,42]. Recent research [27] revealed that the potential of sustainable and unavoidable CO_2 point sources for 2050 can be estimated to be about 165 Mt_{CO2}/a, 95 Mt_{CO2}/a and 607 Mt_{CO2}/a for waste-to-energy plants, pulp & paper mills and the cement mills, respectively, i.e. 867 Mt_{CO2}/a in total. The CO_2 demand for 2068 TWh_{CH4} and 10,379 TWh_{fuels} can be estimated to be 366 Mt_{CO2}/a and 2934 Mt_{CO2}/a, in total 3301 Mt_{CO2}/a. Summing up, a maximum value of 26% of CO_2 demand for synthetic natural gas and FT-fuels could be provided by CO_2 point sources, if all would be utilised for the Transport sector. This highlights the most important role of CO_2 DAC technology [27] for the energy transition in the Transport sector.

The economics of the electricity-based synthetic fuels, i.e. hydrogen, liquefied hydrogen (LH_2), liquefied synthetic natural gas (LNG) and FT-fuels, is of high importance for a successful energy transition in the transport sector, in particular in 2030s and 2040s. Fasihi et al. [43] present an overview on these synthetic fuels for conditions of very good resource conditions as in Patagonia [42] or in the Maghreb region [9] and WACC of 7% as follows: 36 €/MWh for H_2, 42 €/MWh for LH_2, 64 €/MWh for synthetic LNG, 80 €/MWh for FT-fuels, which compares to 78 €/MWh for refined fossil fuels at a crude oil price of 95 USD/bbl [11] (at an exchange rate of 1.3 USD/€), 100 €/t_{CO2} GHG emissions cost [11] and including refinery cost.

The global solar PV capacity demand is driven by the Power sector till around 2030, with contribution by the Transport sector in the already substantially electrified rail segment. However, from 2030 onwards a rapidly increasing share of the global PV capacity demand will be driven by the massive direct and indirect electrification demand of the Transport sector. This goes along with an increasing solar PV supply share in the Power sector and a fast growing electrification share in the Transport sector. Figure 9 shows the additional solar PV demand induced by the electrification of the Transport sector in relation to the Power sector.
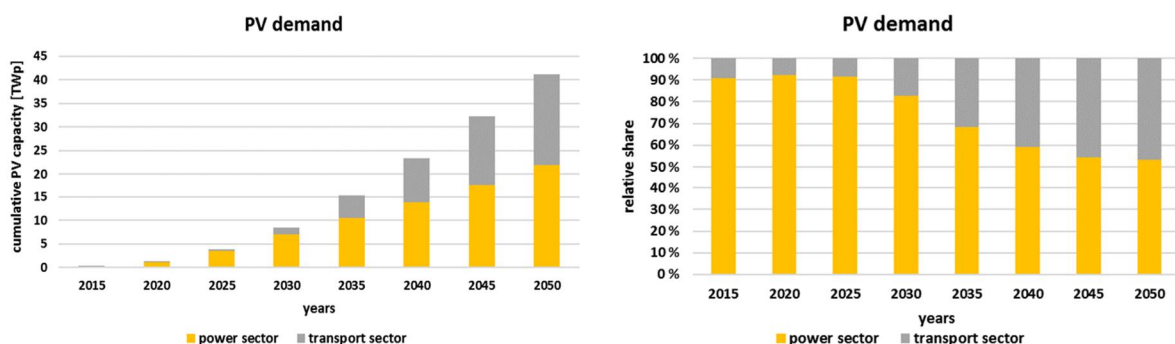

Figure 9: Solar PV demand of the Transport and Power sectors in absolute (left) and relative (right) capacity requirements.

The solar PV supply shares for the Transport and Power sectors follow similar trends, but shifted in time, as shown in Figure 10. The PV supply share in the Power sector rises first, since the electrification of the Transport sector takes some time. The PV supply share in the Transport sector starts to rise steeply from 2030 onwards.
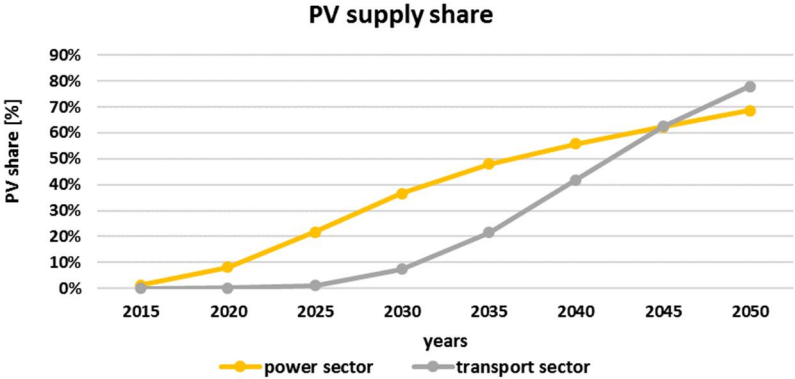

Figure 10: Solar PV supply share for the Transport and Power sectors.

The shifted growth phases of the Power and Transport sectors will most likely stabilise the continued growth and scale-up of the PV industry. The newly added PV capacity per year till 2050 is summarised in Table 4 for 5-year periods. The results indicate that the annual PV market may grow from about 100 GWp in 2017, and the 200 GWp as projected for the year 2020 by the PV Market Alliance [44], to about 500 GWp in the first half of the 2020s. By the first half of the 2030s the annual market size will reach more than 1000 GWp and will stabilise in the 2040s with about 1800 GWp of newly installed capacity per year. The PV demand from the Transport sector stabilises the annual PV installations, as the PV share for the Transport sector grows from less than 10% in the first half of the 2020s to more than 40% in the 2040s. These trends are visualised in Figures 9 and 10. Table 4 also reveals that the relative market share of Europe and North America will decline from 12% and 18% respectively in the beginning of the energy transition to about 6% and 8% respectively, whereas Northeast Asia, with China, and the SAARC region, with India, will represent about 50% of the global PV market.

Table 4: Newly added PV capacity for the 5-years intervals from 2020 to 2050 with breakdown to the contribution of the Power and Transport sector and the nine major regions in the world.

		2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Global newly added PV capacity	[GWp/a]	514	922	1364	1624	1765	1795
share of Power sector	[%]	92%	87%	76%	64%	57%	54%
share of Transport sector	[%]	8%	13%	24%	36%	43%	46%
CAGR of annual PV market	[%]	17%	10%	7%	2.3%	0.9%	0%
share of Europe	[%]	12%	10%	11%	13%	10%	6%
share of Eurasia	[%]	1%	2%	2%	2%	2%	2%
share of MENA	[%]	7%	5%	7%	6%	5%	6%
share of SSA	[%]	3%	4%	4%	5%	7%	9%
share of SAARC	[%]	17%	18%	19%	20%	22%	22%
share of Northeast Asia	[%]	28%	32%	30%	29%	28%	32%
share of Southeast Asia	[%]	11%	11%	11%	9%	10%	10%
share of North America	[%]	18%	15%	12%	12%	10%	8%
share of South America	[%]	5%	5%	5%	5%	5%	4%

The annual solar PV capacity installations reach about 1.8 TWp around the mid of the 21st century, driven by the sectors Transport and Power. Other energy demands for heat, desalination [45], carbon direct removal [27,28] and industrial feedstock [46], such as for cement plants, steel mills, chemical sites and others would be additional. The next research step should cover the remaining demand sectors to gain a more comprehensive view on the total PV capacity demand in the decades to come. The Power and Transport sectors may lead to a total cumulative installed PV capacity of about 41 TWp in 2050. In case the energy sector distribution as of Figure 1 would stay roughly stable, one could estimate the total cumulative installed PV capacity for a fully sustainable energy system in 2050 to be about 80 TWp. The rough estimate for 80 TWp is based on the consideration, that the sectors Power and Transport represent about 54% of the total primary energy demand (Fig. 1), the other energy sectors would require solar PV electricity in a comparable ratio as for the sectors Power and Transport, plus some additional demand for desalination and carbon direct removal. Some to be electrified processes such as space heating via electric heat pumps are more efficient on primary energy basis compared to present fossil fuel solutions, whereas other processes such as power-to-chemicals require more electricity-based than fossil fuel based primary energy, so that the future electricity-based primary energy demand may be comparable to the present fossil fuel based equivalent.

The very high solar PV share of 69% (Power) and 78% (Transport) found by Breyer et al. in 2017 [11] and 2018 in this research can be confirmed by publications of other research teams who apply real world low cost PV to their models. Luderer et al. [47] derived solar PV shares for the entire energy system of about 80% in 2050 and Pursiheimo et al. [48,49] achieved a solar PV share of about 75% in 2050. Both have considered the entire energy system, but none of them in an hourly resolution. The solar energy shares in total energy supply of the three other leading research groups are about 58% (Jacobson et al.) [50], 22-29% (Greenpeace International and German Aerospace Center) [26] and 47% (Sgouridis et al. [51], for the reference year 2050. The IEA still lags substantially behind with a share of 4% for 2040 (18% in the Power sector), according to the latest published data and their most progressive scenario [1]. The International Renewable Energy Agency (IRENA) improves slightly to a share of 26% in the Power sector (numbers for the entire energy system are not disclosed) [52]. It is rather surprising, that even the fossil fuel company Shell shows in its most sustainable energy scenario a solar energy share in the primary energy supply of about 16% in 2050 [53]. This documents a more progressive view than the IEA and maybe even IRENA. All these publications include substantial shares of concentrating solar thermal power generation, but solar PV is regarded the largest solar energy source in all cases. None of the other research teams and institutions have switched their methodology to full hourly resolution, Jacobson et al. show progress in this regard [54], partly using data of Breyer et al. [55,56]. The existing research gap of modelling the entire energy system for very high shares of sustainability in full hourly resolution and high spatial resolution remains for the time being.

The role of biofuels has been kept very strict in this research, since only 4% of the liquid fuel demand has been met by biofuels, a value which is slightly higher than the biofuel contribution

of 3.1% in 2015 [1]. Creutzig et al. [15] pointed out that the total resource potential of bioenergy in total would be 100 EJ (27,880 TWh_{th}), including all forms of biomass and for the entire energy system including bioenergy carbon capture and storage (BECCS). In the Power sector, 8310 TWh_{th} of bioenergy has been allocated as sustainable biomass resource, based on waste, residues and by-products [11,12,13]. The remaining 19,470 TWh_{th} would be based on energy crops. The sustainability of such a high energy crop contribution is discussed strongly (e.g. [16]) and thus limited in scenarios with a very high level of sustainability as explained further by Child et al. [10] and Brown et al. [14]. The 4% biofuel contribution is equivalent to an energy crop contribution of about 2700 TWh_{th}. This is the maximum biofuel contribution during the energy transition and partly met by jatropha plants on degraded land [18]. The bioenergy contribution in this research is more conservative than in Creutzig et al. [15]. This is due to stricter sustainability requirements [10], and the economic competitiveness of biofuels to FT-fuels anticipated by the mid-21st century as illustrated by several sources [9,17, 57].

Future research will have to tackle full hourly resolution for the Transport sector and further investigate the impact on the solar PV demand. Additional effects may be induced by more flexibility due to sector coupling, in particular via smart charging of BEVs but also vehicle-to-grid benefits [58, 59]. Moreover, the high share of indirect fuels, all requiring hydrogen in the first step, may drastically reduce the battery storage capacity demand, since water electrolysers and hydrogen storage can provide additional flexibility, this may lead to even higher solar PV shares in the electricity supply, since less batteries may be needed, which could further reduce cost. A full hourly modelling of the Transport sector will provide further insights on the cost structure of electricity-based energy supply of the Transport sector. Finally, international trade of synthetic fuels can substantially reduce the cost for the remaining liquid hydrocarbon supply [9,41-43,60], with positive effects, in particular on the defossilisation of marine and aviation transportation.

5. Conclusions

Summing up, this is the first study linking fully defossiliated Power and Transport sectors for 100% RE and deriving the consequences for solar PV capacity demand. The electrification of the Transport sector will proceed in three major phases, a first direct electrification till about 2030, a broad indirect electrification via FT-fuels and more usage of liquefied gases (CH_4, H_2) in the 2040s. This projection leads to zero GHG emissions in the Transport sector by 2050.

Solar PV will be the key enabler of the full defossilisation of the Transport sector with a demand comparable to the Power sector but a slightly later growth dynamic. This will lead to a stabilisation of the newly installed PV capacity per year to about 1800 GW in the 2040s. The population rich emerging regions of Northeast Asia, with China, and the SAARC region, with India, will represent about 50% of the global PV market. The corresponding shares of Sub-Saharan Africa and Southeast Asia will increase, while the share of Europe and North America will decline.

The energy sectors, Power and Transport, represent about 41 TWp of cumulative PV demand in 2050. This indicates that the total PV capacity for the entire energy system may reach about 80 TWp in 2050. Future studies have to investigate the other energy sectors in more depth, in particular heat, industrial feedstock demand, seawater desalination and carbon direct removal.

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