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Integration of vertical solar power plants into a future German energy system

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A B S T R A C T

In Germany's future energy system wind and solar power directly cover all electricity demand for more than half of the year. Typical inclined south facing PV modules produce a strong peak around noon on sunny days. In east-west facing vertical PV modules energy yield peaks are shifted towards morning and afternoon hours. Such systems can be applied in agri photovoltaic power plants with similar energy yield per installed capacity to conventional photovoltaic systems. While installed power per area is by a factor 4 to 5 smaller, dual land use with agriculture allows for a technical potential in the terawatt hours per year range, which is comparable to half of entire German primary energy demand. In a simulation model based on the programme EnergyPLAN for Germany 2030 with 80% CO_2 reduction related to 1990 the effect of different PV power plant orientations is investigated. In the model an optimum share of around 80% vertical PV systems is found without any electricity storages and 70% with electricity storage possibilities. It could be shown that vertical PV systems enable lower storage capacities or lower utilization of gas power plants. Without any storage options a reduction of the overall carbon dioxide emissions by up to 10.2 Mt/a is possible.

1. Introduction

In 2015 at the United Nations Climate Change Conference in Paris the parties agreed to pursue efforts to limit temperature increase to 1.5 K compared to pre-industrial temperature [1]. In order to achieve this goal greenhouse gas (GHG) emissions must be reduced rapidly. Greenhouse gas emissions originate mainly from the use of energy, e.g. 85% in Germany [2]. Fortunately, wind and solar energy is abundant and available everywhere. Furthermore, costs for renewable electricity from wind and photovoltaic power plants have plummeted over recent years and today renewable electricity is less expensive than fossil fuel based energy [3]. Unfortunately, wind and solar energy is not available all the time. Solar energy comes with distinct day-night and summer-winter cycles in electricity production. Future energy systems require large quantities of low cost wind and photovoltaic electricity production together with flexibility from transmission lines, demand side management, energy storage and coupling of energy sectors [4–10]. Strong wind and photovoltaic excess capacities could result in so-called "self cannibalisation", i.e. reduced market values in times of high electricity production [11]. Flexibility through sector coupling [12] and proper policies [13] reduce self cannibalisation effects.

Especially in countries with a high number of citizens per area, the area availability for PV power plants is a crucial issue. Often it is discussed whether an area should be dedicated to food production or electricity production. Also due to rapidly decreasing biodiversity, we need more space for promotion of biodiversity [14]. Agri PV (APV) is a concept to combine energy and food production on the same plot of land [15–17]. Two different APV concepts have been developed [18]. First the PV modules are mounted so high, that agricultural cultivation can be done under the modules. The second concept is, where the agricultural cultivation is done between rows of modules. A special case of this concept is, when bifacial modules [41] are mounted vertically, so the area loss is minimized. In order to distinguish solar systems and the energy system, we refer to all solar systems independent of their size as solar power plants in this paper. Several vertical, bifacial solar power plants facing east and west were built on a MW scale by Next2Sun [19, 20] (Fig. 1). The typical solar electricity production peak for around 20–35° tilted south facing (for northern hemisphere) power plants is shifted from noon into morning and afternoon hours. The theoretical potential energy produced from APV systems is very high due to the large availability of agricultural land - up to 1700 TWh/a for Germany [21], more than triple the 2019 (last year before COVID19 impact) electricity demand of around 500 TWh/a [22,23]. The overall electricity yield per kW_p of a plant using vertical mounted bifacial modules can be slightly higher as high as from optimal tilted systems [24], whether it is slightly higher or eventually lower depends on the bifaciality of the used modules, latitude of the installation, diffuse fraction of insolation and ground albedo [25].

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In recent years, plenty of studies about 100% renewable energy supply for Germany have been published [7–9,26]. Also some give an overview about different scenarios [17,27,28]. Most of the studies refer to German climate goals, which have been updated in 2021 [29]. A study published by Agora Energiewende describes a path which is near these updates [6]. Even recently Climate Minister Habeck announced an ambitious goal for the German electricity sector: There shall be 80% share of renewable energy in 2030 and 100% renewable energy supply in 2035 [30].

In simulation of energy systems often only optimum tilted and tracking systems are considered as the vertical system is relatively new on the market [7–9,26]. With better availability of high quality bifacial modules for a reasonable price, first systems on MW scale using this approach were built in Germany financed by the feed in tariff as electricity generation cost is comparable to optimal tilted systems. One example is the 4,1 MW_p plant in Donaueschingen, which produces more electricity than would be expected for a south oriented plant. The higher price of the modules is offset by higher income due to selling electricity [24]. Plants using vertical mounted bifacial modules might not always be aligned facing east-west due to other constraints like topography or geometry of the respective piece of land. In order to account for the impact of different alignments, vertical, bifacial north-south facing systems are also included in the calculations for solar yield.

To evaluate the potential benefits for the energy system from including vertical PV power plants, we use our own, publicly available EnergyPLAN model [31] for the German 2030 energy system at 80% CO_2 reduction compared to 1990. In order to make the effects of module alignment visible, underlying parameters of the energy system model are kept constant. Only two parameters are systematically varied: firstly, the share of installed power of the different PV variants. Secondly, two scenarios are considered, in which either a large-scale electricity storage is integrated or not. Similarly, no tracking facilities have been considered. With the combination of different distributions for PV energy yield, resulting CO_2 emissions as well as the natural gas consumption of gas peaker power plants are compared. Consequently, the effect of shifting solar energy yield itself on the energy system is investigated in this paper in order to estimate the extent to which PV power plants using vertical mounted bifacial modules can contribute to a future energy system.

2. Methods

Energy yield distributions are generated using PVGIS [32]. Germany's energy system is simulated using EnergyPLAN from Aalborg University [30].

2.1. Solar energy yield distribution

In order to evaluate the impact of different solar module orientations on the energy yield distribution, the *Photovoltaic Geographical Information System* (PVGIS) from the Joint Research Center of the European Commission is used [32]. All distribution data is generated for the year 2015 in hourly distribution. A fixed elevation is used as the mounting type and crystalline silicon as the module type. System losses are given as 13%. In all cases the average energy yield is calculated at four different locations in Germany (Hamburg - North, Chemnitz - East, Munich - South, Saarbrucken - West). These profiles are merged into one resulting profile for each elevation variant by averaging profiles of each location.

The energy yield distribution for inclined south facing solar power plants (i-S) was calculated at a module tilt angle of 20° as this is often used for PV plants, which are optimized on financial parameters i.e. investment cost and area costs. The yearly energy yield for the i-S power plant is 1020 Wh/W_p. For the vertical, bifacial solar power plants energy yields for two solar modules facing east and west (v-EW) or north and south (v-NS) are calculated and the hourly sum of both is used in all subsequent calculations. Bifaciality is assumed as 90%, i.e. the rear side of the modules has 90% of the front side Standard Test Conditions (STC) power. In case of the v-EW power plant bifaciality is distributed to both east and west, i.e. 95 % of STC system power is available on either side. The yearly energy yield is 999 Wh/W_p. Measured energy yield data from Next2Sun show that the energy yield from real vertical power plants can be slightly higher than calculated from PVGIS [24]. The Albedo from the ground might not be integrated well in the PVGIS simulation algorithm leading to lower yield values compared with measured data. For further calculations we use PVGIS data so the effect might be underestimated. For the v-NS the rear side of the module is always facing north. Table 1 lists the different solar power plant variants, their alignment characteristics and yearly yields. In addition to the sole analysis of the electricity generation profiles of all PV system types, a combined profile with the shares 25% i-S, 50% v-EW and 25% v-NS is determined as an

Fig. 1. Vertical, bifacial agri photovoltaic power plant (APV) [19].

Table 1
Slope and azimuth for all solar power plants in PVGIS.

Parameter	i-S	v-EW	v-NS	25/50/25 combination
Slope	20°	90°	90°	mixed
Azimut	0°	−90° and 90°	0° and 180°	mixed
Yearly yield	1020 kWh/kW$_p$	999 kWh/kW$_p$	926 kWh/kW$_p$	986 kWh/kW$_p$

example to illustrate the coupling of the distributions.

2.2. Energy system simulation

In addition to the electricity yields from differently oriented solar systems, a future energy system model forms the basis of the study. The objectives for the energy system are explained in more detail in the following. To reduce GHG emissions, the reference year 1990 is set at 1249 MtCO$_2$eq/a (not including land use, land use change and forestry). The largest share of emissions, 83% (1037 Mt/a), is attributed to energy-related emissions, which are characterized by the burning of fossil fuels. Industrial processes account for 8% (97 Mt/a), agriculture for 6% (77 Mt/a) and waste management for 3% (38 Mt/a) of CO_2 emissions [33]. Germany's previous climate targets were stated at 55% reduction compared to 1990, according to the Climate Protection Act 2019. In May 2021, the law was updated and tightened to 65% CO_2 reduction [29]. However, on the basis of the worldwide CO_2 budget for 1.75 K/67% probability, a german budget of approx. 6.7 GtCO$_2$ from 2020 was calculated by the German Advisory Council on the Environment (SRU) (4.2 GtCO$_2$ for 1.5 K/50%) [34]. According to this, a reduction of greenhouse gas emissions by 2030 of at least 80% compared to 1990 is needed (Fig. 2). This corresponds to well below 250 MtCO$_2$eq/a by 2030 as a targetable value on the way to climate neutrality. In this regard, it should be noted that no exports or imports of electricity are taken into account to achieve the goals, in order to consider a scenario that is as conservative as possible.

Based on the mentioned goals an energy system model for Germany in 2030 aiming for 80% CO_2 reduction is generated using EnergyPLAN [31]. Since EnergyPLAN only considers CO_2 as a GHG, the entire target values for 2030 are equated to CO_2 as a climate gas. The energy system model is available publicly as download from EnergyPLAN website under existing country models as well as in the supplementary material of this paper with different data formats (Appendixes B – D). In order not to go beyond the scope of this publication, key strategies for achieving the mentioned CO_2 target are explained in the following. More detailed explanations are given in the related documentation in Appendix A.

In the heating sector heat pumps and electric heating replace more than half of fossil fuel boilers. In the transport sector battery electric vehicles account for twice the number of kilometres from diesel and petrol combustion engines. Electric and hydrogen drives replace about 70% of fossil fuels. Consequently, the large-scale climate-neutral production of hydrogen by means of electrolysis plays a major role in reducing CO_2 emissions and guaranteeing security of supply. Hydrogen is an important energy carrier for the operation of flexible gas-fired power plants that compensate for supply sinks due to an energy system based on variable renewable energy sources.

In the electricity sector all power plants and combined heat and power (CHP) plants are fueled by natural gas. Nuclear and coal exits are completed. The share of renewable energies in the electricity sector has increased to approx. 80%. 150 GW of onshore wind power and 45 GW of offshore wind power are installed. 400 GW of photovoltaic power plants are split between different energy yield distributions that were previously calculated for the four German locations. Furthermore, geothermal plants are being expanded on a large scale both for heat supply (15 TWh/a) and for electricity supply (97 TWh/a). An electrical storage with 1 TW power and 1 TWh capacity is applied to give the system (if integrated) a high flexibility in the short term. This is a simplified assumption and means that electrical storage power is not limiting storage utilization. In a cost optimized system lower storage power is required [43,44]. For sake of simplicity this includes different types of storage, i.e. batteries, additional pumped-storage hydropower plants, redox-flow batteries and also electricity storage through reconversion of hydrogen in gas power plants. In our model electricity demand for 2030 increases to 1214 TWh/a and depends mainly on the assumptions for energy saving and fuel switch. The greatest uncertainties are in the heat supply for buildings and industry. Needed wind and PV system capacities in Germany also depend to a large extent on import of energy. Still, the capacity of wind and PV power plants in

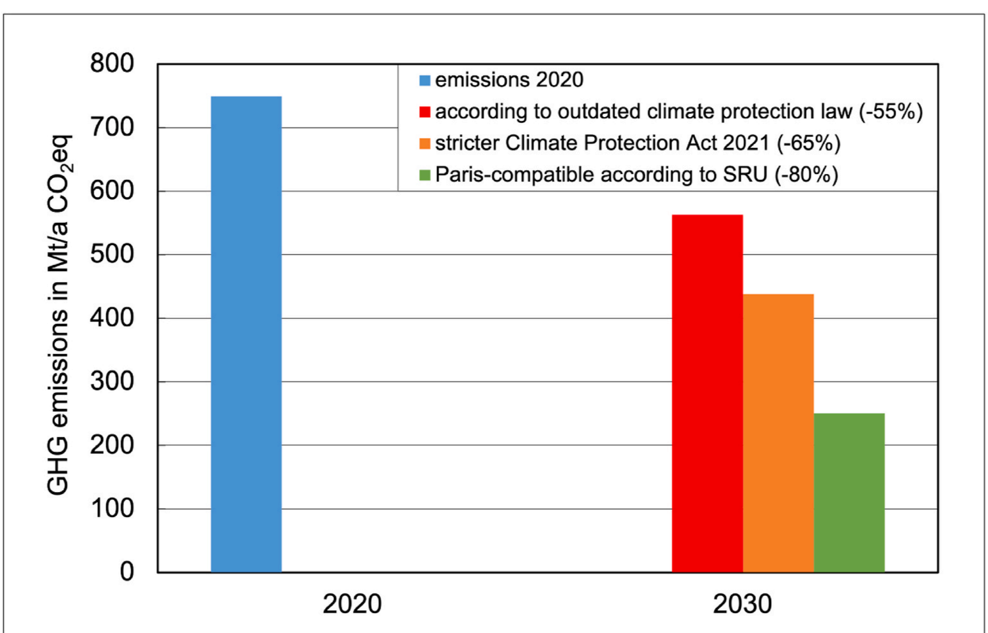

Fig. 2. GHG emissions in 2020 and varying goals for 2030. German climate protection measures are not compatible with the Paris Agreement (1.75 K CO_2 budget) and well below the 1.5 K target.

our model corresponds well to findings of other studies with ambiguous climate goals for 2030/35. Based on findings of various 100% renewable energy supply studies with different target years, a capacity of 150 GW Wind and 350 GW PV is suggested 2030 in Gerhards et al. to meet a CO_2 Budget of 6,7 Gt from 2020 on [35,39,40]. Finally, CO_2 emissions are reduced to the desired level of 227 Mt/a if the electricity storage and 100% south-facing PV systems are integrated in the mentioned EnergyPLAN model.

In order to analyze the potential benefits for the energy system from the inclusion of vertical solar power plants facing east and west, the underlying parameters of the energy system model are kept constant. Only two parameters are systematically varied: firstly, the share of installed capacity of different PV alignments. Secondly, two scenarios are considered in which either large-scale electricity storage is integrated or not. Likewise, no tracking devices and costs associated with the energy system were considered. With the combination of different distributions for the PV energy yield, CO_2 emissions, produced electricity from solar power plants as well as the natural gas consumption of gas-peaker power plants resulting from EnergyPLAN are compared and analyzed. In our work, we do not want to present another pathway for the energy system, but we want to describe a situation in which the impact of different generation profiles of the vertically mounted bifacial PV system is visible. Therefore, we did not compare optimized scenarios but take the CO_2 emission of gas fired power plants as an indicator of the varied PV generation profiles.

3. Results

In this section, the solar data are evaluated on the one hand, and the effects of changing solar module orientation on the 2030 energy system model are examined on the other hand.

3.1. Solar yields of varying module orientation

When comparing energy yields of different module orientations, differences in temporal power distributions become apparent. A sunny summer day is shown as an example in Fig. 3. For 20° tilted south facing solar power plants (black), maximum power is 0.76 W/W_p at 11 a.m. Overall, the power plant generates electricity from 3 a.m. to 7 p.m. (assuming no summertime). A bifacial PV power plant facing east and west (green) shows two peaks in the morning at 7 a.m. and in the afternoon at 4 p.m., each at a specific power of 0.69 W/W_p in the morning and 0.68 W/W_p in the afternoon. At 11 a.m. a minimum of 0.24 W/W_p is visible, when direct insolation is only at the edge of the module and only indirect insolation is collected. For this alignment electricity generation in the morning and evening hours is higher than in case of inclined south facing modules. V-NS facing solar power plants (blue) generate overall 27% less electricity on a sunny summer day in comparison to i-S power plants (Table 2). Two peaks of 0.18 W/W_p occur at 5 a.m. and 6 p.m. due to the influence of the north facing solar module side. Furthermore, an overall smaller peak at noon of 0.59 W/W_p is evident. If the orientations of modules mentioned above are combined in terms of generation, the result is a profile that combines advantages and disadvantages of the power plants. Splitting of the power to 25% i-S, 50% v-EW and 25% v-NS solar power plants (gray dashed) a steady and broader generation curve throughout the day is the result, which is dominated in particular by v-EW power plants. The high midday peak is damped by the lower electricity production of the v-NS power plants.

The power generation profile on a sunny winter day of the power plants mentioned above are shown in Fig. 4. I–S power plants reach a maximum peak of 0.41 W/W_p at 11 a.m., which is more than 50% compared to maximum power in summer (black). Electricity production ranges from now 7 a.m. to 4 p.m., i.e. 7 h shorter than for the sunny summer day. For v-EW power plants two peaks are visible at 9 a.m. and 2

Table 2
Example of energy yields from power plants of different orientations on a sunny summer and winter day.

Alignment/day	Summer day yield in Wh/W_p	Winter day yield in Wh/W_p
i-S	6.3	2.2
v-EW	7.5	1.7
v-NS	4.6	4.0
25/50/25 combination	6.6	2.4

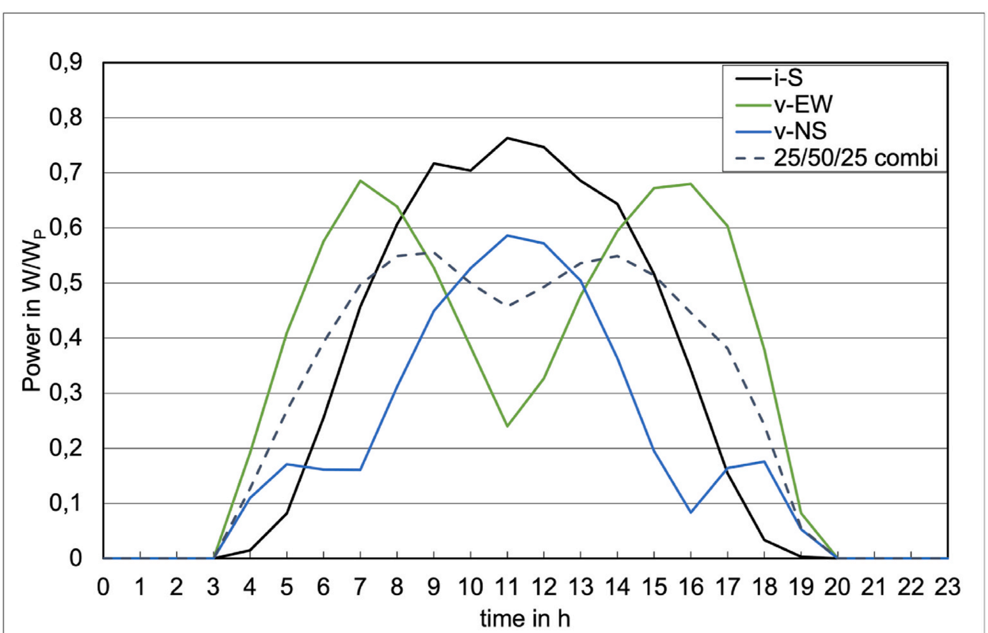

Fig. 3. Photovoltaic electricity production on a sunny summer day with different orientations. Generation of electricity with inclined south (i-S) and vertical east-west (v-EW) PV power plants can complement each other. Vertical north-south (v-NS) power plants achieve overall lower yields. A combined system of 25% i-S, 50% v-EW and 25% v-NS shows well balanced generation between 7 a.m. and 4 p.m.

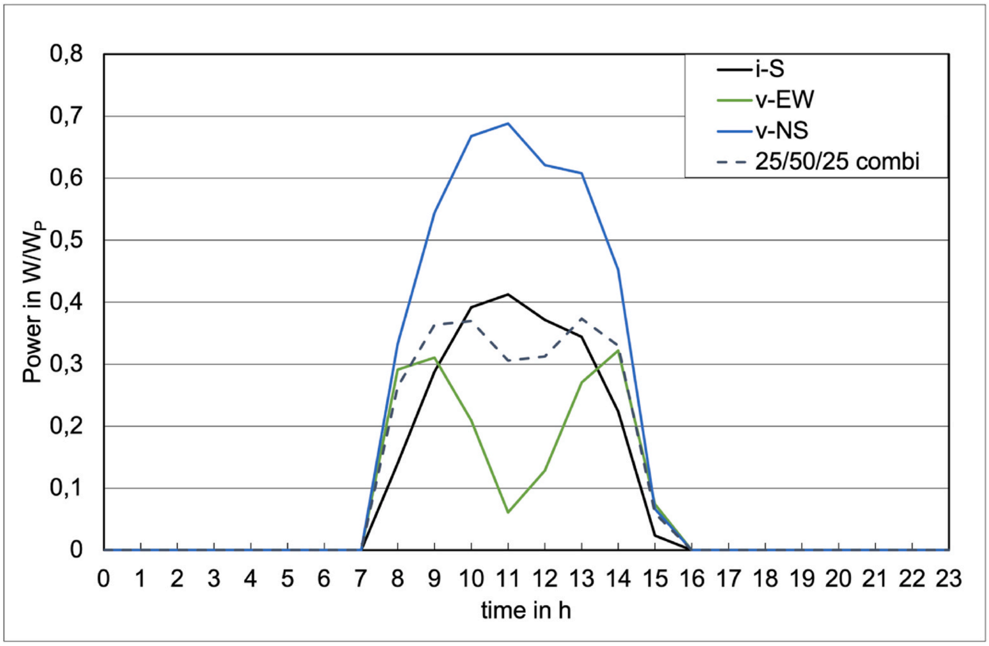

Fig. 4. Photovoltaic electricity production on a sunny winter day with different orientations. Generation of electricity with inclined south and vertical east-west PV power plants is low. Vertical north-south power plants achieve the highest yields.

p.m., each at a specific power of 0.31 W/W_p in the morning and 0.32 W/W_p in the afternoon. Those power plants achieve less than 50% of the maximum power on a summer day (green). Minimum power is generated at 11 a.m. with 0.061 W/W_p. V-NS oriented power plants reach 0.69 W/W_p at this time (blue). This value corresponds roughly to the maximum power generated by the i-S power plant on a sunny summer day and is larger than for the v-NS power plant in summer. The reason for this larger power peak in winter is due to the low altitude angle of the sun in winter and the resulting steep angle of incident on the v-NS modules of direct sunlight and lower temperature during winter. These two effects overcompensate for overall lower insolation power for the v-NS power plants. However, also for the v-NS power plant the generation duration at this time of year is also limited between 7 a.m. and 4 p.m. due to sunshine duration. If solar power plants are combined in share of 25% i-S, 50% v-EW and 25% v-NS on a sunny winter day, higher yields can be achieved than for purely southern or vertical east-western systems because of advantages from v-NS orientation (gray dashed).

In Table 2 daily energy yields can be compared for different orientations of solar modules in the power plant on the selected days. V-EW power plants generate the highest energy yield on the summer day with 7.5 Wh/W_p and the lowest energy yield on the sunny winter day at 1.7 Wh/W_p. While v-NS power plants have by far the lowest energy yield in summer at 4.6 Wh/W_p they can provide almost as much energy on a sunny winter day with 4.0 Wh/W_p. Even only from this table for two sunny days it is found that the combination of different power plants can lead to excellent results with good energy yields on sunny summer and

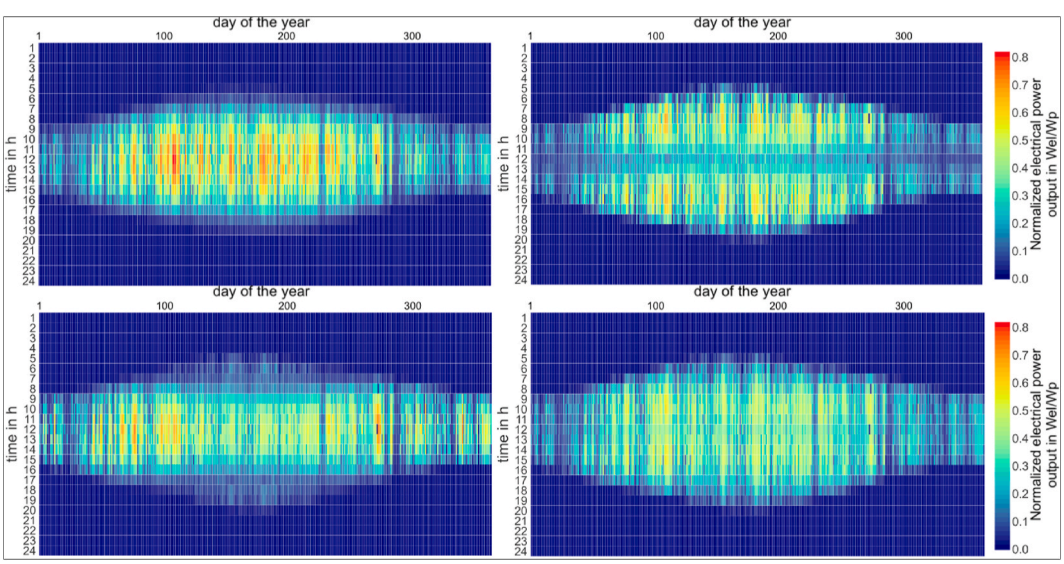

Fig. 5. Normalized electrical power output in W_{el}/W_p for i-S (top, left), v-EW (top, right), v-NS (bottom, left) and a 25/50/25 combination (bottom, right) of the mentioned PV systems. i-S systems show the highest yields in the middle of the day and year, v-EW have two clearly visible maxima in the morning and evening hours in summer, v-NS systems show the highest yields at midday in the first and second third of the year. The combined variant shows a generally more even electricity generation with lower peak yields.

winter days.

If the electricity yields of all PV systems and the combined variant are plotted over the exemplary year 2015 and the time of day, this results in Fig. 5. The respective profiles show the effects mentioned above: I–S systems generate the highest peak yields in the middle of the day and year, followed by v-NS systems in spring and autumn and v-EW systems with maximum yields around 8 a.m. and 4 p.m. in summer. The combined variant shows overall lower peak yields and a more even power generation profile. Furthermore, the minimum of the v-EW systems is visible in hour 12 (corresponds to 11 a.m.). Unlike i-S and v-EW systems, v-NS generate lower yields in summer than in spring and autumn. Between 4 and 6 a.m. and 4 and 6 p.m. low yields of approx. 0.1 to 0.2 Wh/W_p are generated by reflective and diffuse radiation over the two module sides.

If the energy yields are compared on a monthly level, tendencies of the selected days are the same (Fig. 6). In summer the highest yields are achieved by i-S and v-EW. I.e. In July i-S power plants generate 141.7 Wh/W_p while v-EW power plants produce 2% higher energy yields with 143.9 Wh/W_p. V-NS power plants, on the other hand, achieve about 99.7 Wh/W_p. In December 57.0 Wh/W_p can be generated with v-NS power plants. Compared to the energy yield of v-EW power plants with 25.8 Wh/W_p v-NS power plants produce more than twice as much electricity. I–S facing power plants produce 35.6 Wh/W_p and thus 60% of the amount of v-NS power plants. Since winter tends to have fewer sunny days and an overall short electricity production period, all power plants produce less in winter compared to summer. The summer winter difference is by far the lowest for v-NS power plants due to their reduced energy yield in summer and increased energy yield in winter.

Advantages of v-NS power plants in winter become visible in Fig. 7 when monthly yields are normalized to generation of i-S power plants (corresponds to 100%). Those power plants achieve 40–60% more power in winter than i-S facing power plants. Consequently, the potential of v-NS orientation is assumed in seasonal electricity balancing. Comparing the yields of v-EW power plants with those of i-S solar power plants the amount of yearly electricity yield is comparable. Monthly yields are maximum 28% lower in winter and 5% higher in summer. However, the primary advantage of the v-EW orientation are the generation profile during a day and the lower space consumption.

An annual duration curve, in which the power is sorted in descending order, is shown in Fig. 8 for each of the three types of power plants. The annual duration curve of i-S power plants has a higher slope with the highest loads up to 0.82 W/W_p. Stabilizing effects by v-EW power plants become apparent from the crossing point with i-S output at 0.26 W/W_p. While v-EW power plants generate at least 0.13 W/W_p for 3000 h, i-S power plants only generate 0.10 W/W_p for this time. The annual duration curve of the v-NS elevation has the lowest yields, as the curve follows the lower ranges of the other duration curves.

Comparing the specific annual yields in Table 1 (see section 2.1) v-NS power plants reach an amount of 926 Wh/W_p in our calculation. This corresponds to 94 Wh/W_p i.e. 9 % less annual electricity production compared to i-S power plants. Due to this fact v-NS solar power plants are not considered in the following chapter. Vertical east-west power plants, on the other hand, generate 999 Wh/W_p according to the PVGIS simulation and thus almost comparable amounts of i-S electricity. Therefore, the focus is on the analysis of varying shares of i-S and v-EW solar power plants in the energy system model.

3.2. *Influence of PV power plant orientation on the German energy system 2030*

In order to quantify the potential impact of solar power plants with vertical modules facing east and west on the future energy system the described PVGIS solar datasets are integrated into our Germany's energy system 2030, which gives 80% CO_2 reduction compared to 1990. Embedding in EnergyPLAN is done as distribution files with hourly values for the reference year. In total, an installed photovoltaic capacity of 400 GW_p was assumed in the EnergyPLAN model and is retained for combinations of power plants with different module orientation. Due to the difference in specific energy yield of the different plant types the total PV energy yield changes with different distributions of PV power between the different systems. As a result, a larger share of v-EW power plants leads to decreasing PV electricity production.

In the model i-S solar power plants are gradually replaced by v-EW power plants in 10% share steps. In Fig. 9 carbon dioxide savings from the energy systems are plotted for a v-EW po-wer plant share from 0% to 100%. With a v-EW share of 70% with an electricity storage and 80% without this storage option CO_2 emissions become minimal and are 2.1 Mt/a and 10.2 Mt/a lower than without v-EW power plants,

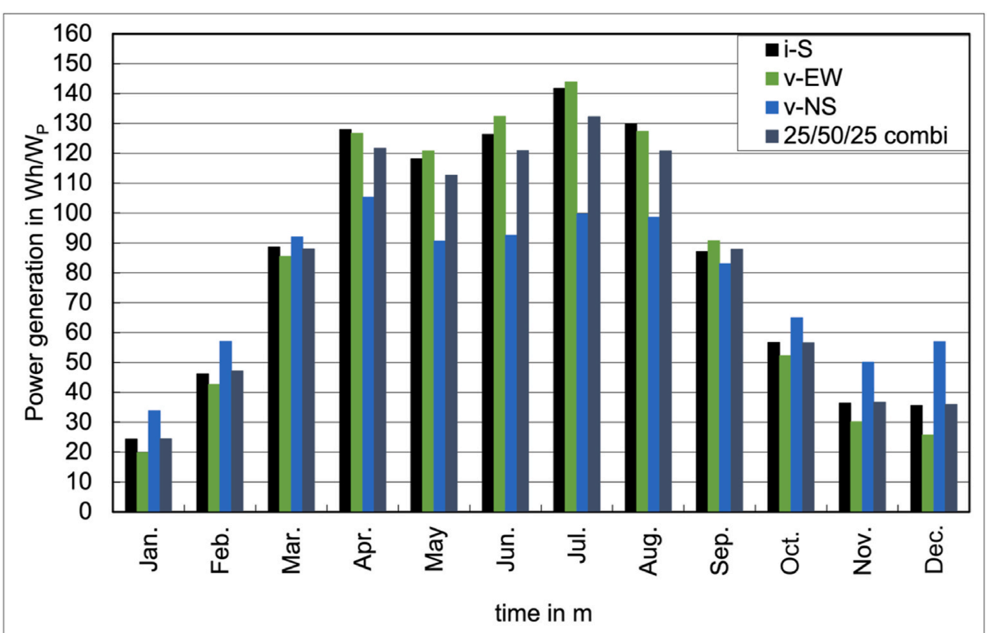

Fig. 6. Monthly photovoltaic electricity production of power plants with modules in different orientation. In summer, yields are slightly higher with vertically east-west power plants. In winter, vertical north and south facing power plants show the highest electricity yields.

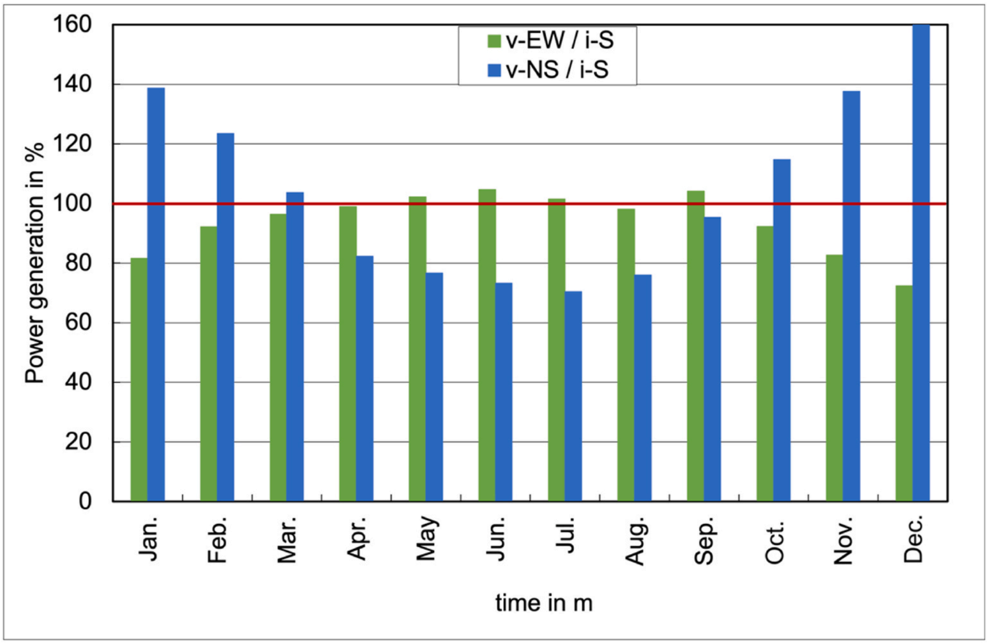

Fig. 7. Monthly photovoltaic electricity production of v-EW and v-NS orientation normalized to the monthly amount of electricity from power plants with inclined south facing modules. Energy yields of v-EW power plants are comparable to those of i-S power plants. V-NS power plants produce higher yields in winter and lower yields in summer.

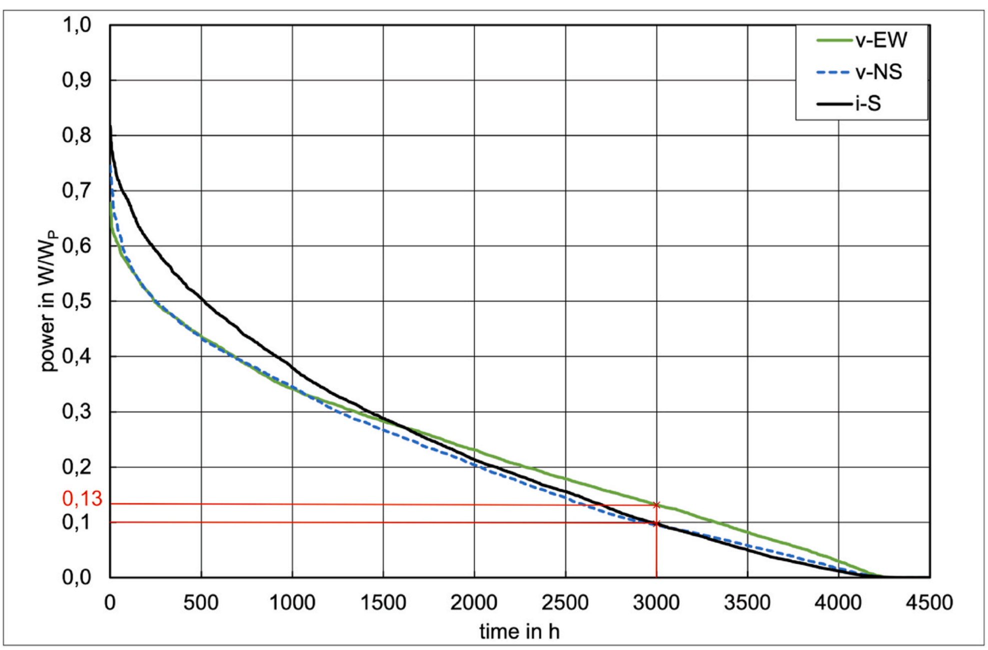

Fig. 8. Annual duration curve of power plants with varying module orientation. Vertical east-west power plants generate more electricity in the lower power spectrum (below 0.26 W/W$_p$) than inclined south power plants. On the other hand, i-S power plants reach higher peak powers (above 0.26 W/W$_p$) more often. Vertical north-south power plants do not show any significant advantages in a direct comparison.

respectively. While the total number of CO_2 emission reduction might seem small relative to absolute emission it still corresponds roughly to 5 times (without electricity storage) and the same amount (with electricity storage) the emissions of the German domestic air traffic, which is valued at approx. 2.1 Mt/a [36]. Causes of the CO_2 reduction potential of v-EW plants in combination with i-S plants are investigated and explained in more detail below.

Fig. 10 shows a comparison of the theoretically possible PV electricity generation (yellow) with the amount of electricity actually generated in the energy system model with (blue) and without the integration of battery storage (red) with varying shares of v-EW systems. While the integration of battery storage leads to a constant PV electricity generation in dependence of the PV system mix, the scenario without electricity storage shows a maximum PV electricity generation with 80% v-EW share. This fact can be explained by the broader generation profile in the summer months and an overall steadier electricity generation throughout the day (see section 3.1), so that more of the PV electricity can be directly assigned to electricity demand. This trend is also

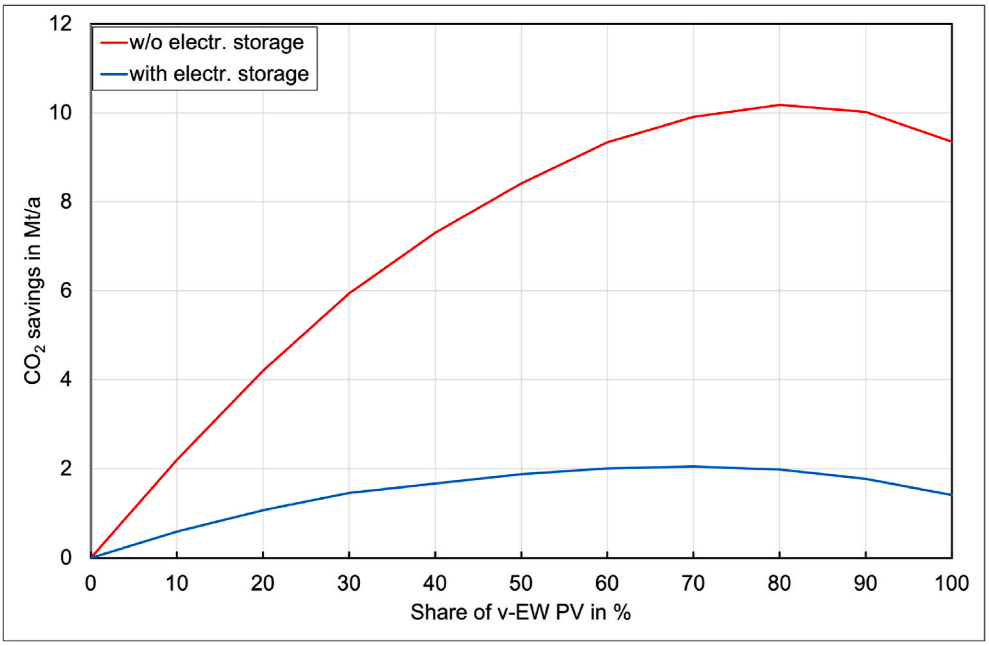

Fig. 9. CO_2 savings in the German energy system in 2030 with varying shares of v-EW PV power plants. Carbon dioxide emission are reduced to a minimum at 60–80% v-EW and are up to 10.2 Mt/a lower than without v-EW. Battery storages significantly reduce the possible savings as electricity can be provided from storage instead of gas fired power plants.

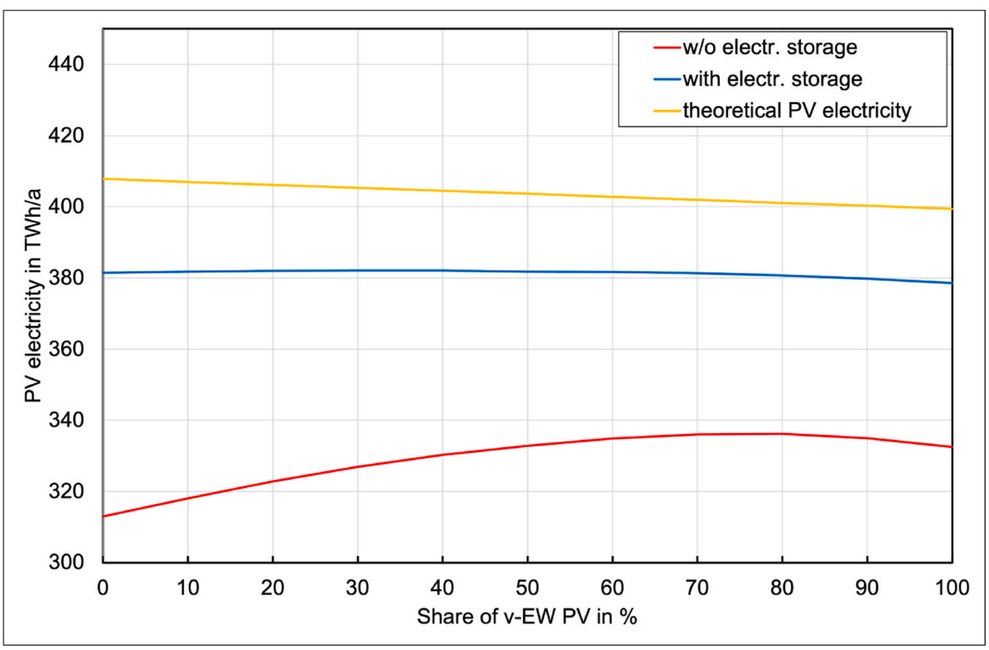

Fig. 10. Comparison of PV electricity generation as a function of v-EW share. Yellow is the theoretical PV generation without curtailment, higher v-EW share reduces slightly the electricity generation due to lower energy yield of the v-EW plants. In a system with electricity storage PV generation is fairly constant. Without electricity storage curtailment of PV plants is about 23.3 TWh/a lower with higher v-EW share resulting in a peak of PV electricity generation at 80% v-EW share. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reflected in Fig. 9, because the more electricity from PV is used, the higher the CO_2 savings because less electricity has to be generated from fossil energy sources to meet the same electricity demand. Both considerations imply that PV energy is curtailed, as the curves are below the theoretically producible amount of electricity. However, the curtailment is significantly lower with battery storage. Thus, with 100% i-S systems, 68.5 TWh/a more electricity is used from PV systems with than without integrated battery storage. This results in a difference in CO_2 emission of 40.2 Mt/a.

If an electricity storage system is integrated into the model, there are hardly any noteworthy differences in PV electricity generation for e.g. 100% i-S and 70% v-EW. However, a closer analysis shows a similar effect as in the scenario without battery storage: With 100% i-S systems, 117 TWh of electricity are temporarily stored, while with 70% v-EW it is only 94 TWh and thus 23 TWh less. Since intermediate storage is associated with electricity losses totalling approx. 29%, this alone results in 6.6 TWh more electricity being lost than in the energy system variant with 70% v-EW plants. Since the electricity demand remains constant, such differences must be covered either by other renewable energy sources such as wind or by gas-fired power plants. Finally, in both scenarios, the annual PV electricity generation at 100% v-EW is slightly lower than at 100% i-S, due to lower overall annual yield of the PV generation.

Due to high electricity generation in the morning and evening hours during days in summer, a combination of v-EW and i-S systems has the potential to directly cover a higher share of daily electricity demand and – if included – charge battery storage for a longer period of time. In both cases, the result is lower electricity generation from gas-fired power plants, although the effect is smaller when battery storage is integrated. These effects can be demonstrated when looking at the electricity production from flexible power plants using natural gas. Fig. 11 shows the difference in electricity generation from gas power plants between an energy system with a share of 100% i-S and an energy system with 80% v-EW and 20% i-S power plants without any battery storage (above) and between an energy system with a share of 100% i-S and an energy system with 70% v-EW and 30% i-S power plants with battery sto-rage (below). Positive values represent savings for the 80/20 and 70/30 energy systems, negative values represent additional gas consumption yields in of the fossil power plants.

For the scenarios 70/30 with and 80/20 without storage, electricity generation in the midday hours is usually sufficiently high to cover the electricity demand at that time, despite the lower proportion of i-S plants, so that no gas-fired power plants need to be switched on. An increased electricity storage level allows fluctuations between load and renewable generation to be balanced out for longer in the short to medium term. The advantageous effect of the v-EW plants becomes apparent for both the scenarios without and with battery storage in a period from March to October. There is an additional demand for power plant electricity in summer for the 100% i-S power plant but less in winter. In total, electricity of about 20.4 TWh/a without and 3.6 TWh with storage from flexible power plants can be omitted annually because of a v-EW orientation of 80% and 70% of solar power plants,

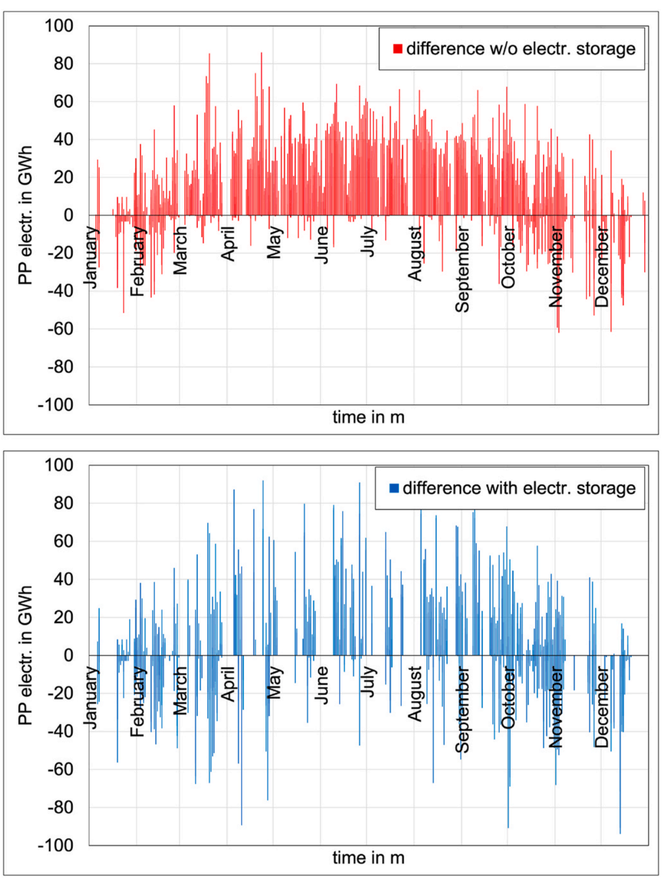

Fig. 11. Electricity generation difference in natural gas-fired power plants at 100% i-S and 70% v-EW and 30% i-S facing solar power plants without storage (above) and 100% i-S and 80% v-EW and 20% i-S facing solar power plants with battery storage (below). In summer, larger amounts of power plant electricity are saved than have to be additionally generated in winter.

respectively. This results in CO_2 savings of up to 10.2 Mt/a without and 2.1 Mt/a with storage (see Fig. 9). In combination with a reduction of 2 TWh in electricity generation by CHP, the resulting CO2 savings amount to 8.6 Mt/a.

Fig. 12 shows the load duration curve for the energy system model for a 80% CO_2 reduction. The residual load curve, i.e. load minus wind and solar power in each hour, for 4 different systems with 400 GW PV are also shown. These systems are:

(1) 0% v-EW (i.e. 100% i-S) without electricity storage
(2) 0% v-EW with electricity storage
(3) 70% v-EW with electricity storage (optimum value)
(4) 80% v-EW without electricity storage (optimum value)

Electricity storage in cases (2) and (3) is still 1 TW power (both charging and discharging) and 1 TWh storage capacity. Positive residual load means that additional sources must provide electricity (both storage and gas peakers). Negative residual load corresponds to overcapacity which can be stored or used for other sectors like mobility, heating and hydrogen electrolysis. The transition from positive to negative residual load is shifted for the energy systems with or without v-EW share. While systems with 0% v-EW share have 3667 h of positive residual load, systems with 70% and 80% v-EW reduce this time to 3388 h and 3363 h, i.e. time electricity production surplus is extended by 279 h and 304 h, respectively.

While v-EW shifts the residual load curve at the lower half of hours to the left. The use of extra electricity storage allows for much more negative loads at the very end of the residual load curve. When no use for wind and solar overcapacity is required wind and solar are dispatched, i.e. partially shut down. Both systems without electricity storage limit negative residual load in our energy system to above −75 GW at all times. Both systems with electricity storage enable use of wind and solar power to below −215 GW and −290 GW with and without v-EW, respectively.

4. Discussion

APV has a huge potential for contributing to the renewable energy transition. Vertical APV is particularly attractive because it shifts solar yield into hours of higher electricity demand. In this paper we investigate the potential impact of successful implementation of large-scale v-EW PV on a future energy system. Combinations of i-S and v-EW PV systems distribute the electricity supply more evenly over the course of the day. Combining the energy system with v-NS photovoltaics leads to more electricity supply in the winter months. This means that the number of hours requiring electricity from other sources than wind and PV is reduced - in our models by up to 300 h. We also find that overall PV electricity usage is increased with v-EW due to a reduction in curtailment. The benefit of v-EW is larger with lower energy system storage capacity. With large electricity storage, i.e. with very little PV curtailment, the benefit from v-EW is neglectable or no longer existent. Thus, v-EW can be useful from an energy system perspective and might lead to reduced optimum system cost depending on the applied boundary conditions. For the assumed battery storage with 1 TW power and 1 TWh capacity, it was forced that the electrical storage capacity does not limit the storage use. In a cost-optimized system, however, smaller dimensions of the storage parameters are required [43,44]. The combined benefit from difference in yield distribution and the increased huge potential for installation in agricultural land leads to a recommendation to integrate PV systems with nonstandard distributions in future calculations for optimization of 100% renewable energy systems [27,42].

Initial APV research focuses on PV systems installed above agricultural land [16]. New generations of solar cells and modules in the mainstream market like PERC and HIT cells provide bifaciality with little or no extra cost [37]. Bifacial modules enable the use of vertical PV systems in rows alternating with agricultural land use. Both fixed

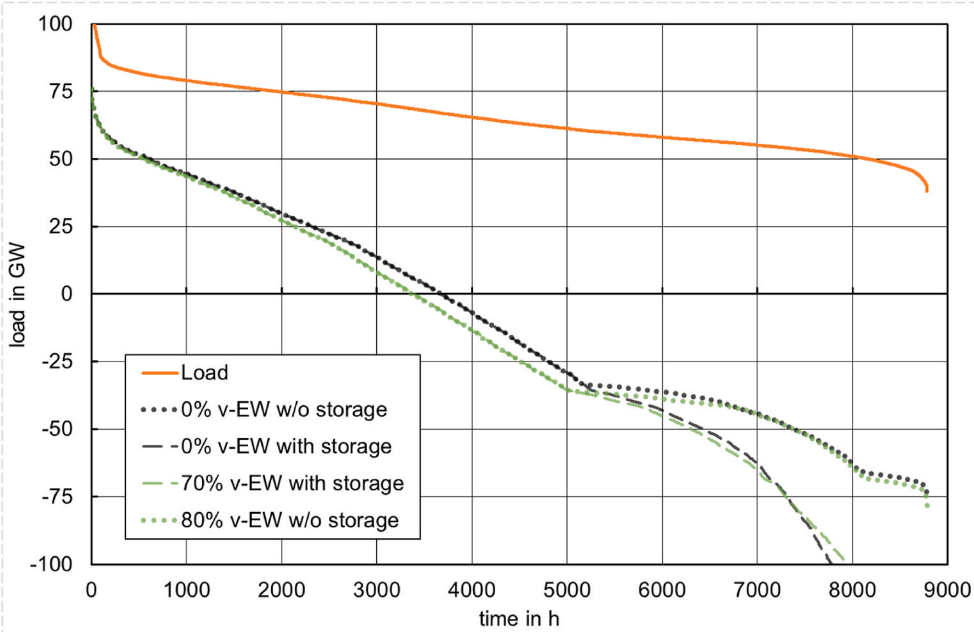

Fig. 12. Annual electric load and residual load duration curves from Germany 2030 model. All systems use 400 GW PV power, the black curves have all inclined south systems while the green curves have 70% and 80% share of vertical east-west PV. The latter show lower residual loads between 2000 h and 5000 h. Systems without storage (dotted lines) never show residual load below −75 GW, whereas electric storage with (dashed lines) enables negative residual loads below −200 GW. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mounting and single-axis tracking is possible for such systems [38]. Our investigations focus on fixed mounted tilted systems. Nevertheless, the consideration of such a system with tracking options should be investigated on a large scale in further research.

The cost of vertical bifacial APV is slightly higher than for standard inclined PV. This is - so far - due to higher module costs. Also the installable power per area is lower due to shading effects. Rows of vertical APV should be installed 8 m–12 m apart. This results in increased cost for wiring. The additional cost for the land itself must be shared with the retained agricultural land use or benefit due to biodiversity promotion. If electricity is sold on the power exchange market (EEX) the potential revenue for vertical bifacial PV with energy yield peaks in morning and afternoon in Germany is currently higher [24]. For example, the average market value in 2021 in Germany at 9 a.m. was 18% higher than at 12 o'clock [22].

The intention of this paper is by no means suggesting for all utility PV systems being vertically mounted in future. Much rather a new opportunity is highlighted. Vertical APV can support the overall energy system. While PV power generation is only available when the sun's out, generation peaks can be shifted away from midday peak without large detrimental effects on energy generation and electricity costs. Furthermore, vertical APV can enable dual land use allowing for simultaneous production of food and energy as the direct area demand is very low. This can also grant photovoltaic energy producers' access to agricultural land, especially green land. If this is done properly and in the context of social acceptance discussion vertical APV has the potential to strongly increase the land area available for photovoltaic utilities because food and energy production on the same area are possible.

The presented calculations make use of a series of simplifications. The energy system model with EnergyPLAN is not optimized (e. g. no specific integration of smart charging electric vehicles and vehicle-to-grid options) but based on our own assumptions and research. No electricity import or export is possible in our model, which would improve the results of the energy system simulation. No cost optimizations were considered for the energy system model. The energy yield distributions with PVGIS at an hour distribution are fairly coarse and a series of effects like shading and degradation are not considered. Measured energy yield data from Next2sun shows that v-EW power plants can deliver a slightly higher yield than i-S power plants [24]. The data sets generated in this simulation represent a conservative view, which is presumably due to simulation parameters that cannot be viewed in PVGIS. Furthermore, only four discrete locations in Germany are considered. Overall, it should be mentioned that no cost assessments were made in this work. This aspect is to be addressed in further considerations of v-EW plants in the energy system.

60–80% of vertical PV power plants in the energy system appears to be a very large share, but as shown above, adding v-EW power plants at low share makes large differences. Furthermore, there is high potential as vertical APV enables significant land use, especially when combined with automation in agriculture. Extra financial earnings from the PV systems as well as the opportunity for green energy on the field for various applications might make APV systems attractive. Moreover, other applications for vertical PV might become attractive in the future, these include facades in building integrated PV (BIPV) as well as sound barriers and other PV systems alongside traffic infrastructure such as roads and railways. It is expected that ambitious development goals in Germany will enable new innovative types of PV systems. Proper market incentives will select the right type of PV power plants giving the largest benefit to the energy system overall.

Finally, comparable measured energy yield data is lacking for the vertical north-south power plants. Due to the lower calculated overall energy yield and the lack of measurement data v-NS power plants are not considered further in this paper. Nevertheless, it is to be checked if v-NS power plants could be beneficial for seasonal balancing in the future. This could be especially important for areas with low wind potential.

5. Conclusions

In order to limit climate change to below 1.5 K, the large-scale increase of renewable energies in the German energy system is necessary. The most important sustainable sources of electricity are wind and solar power plants, whose variable electricity generation poses challenges for the current energy system in terms of security of supply, load management and storage and sector coupling. Typically, solar plants are installed with an inclination of about 20–35° to the south to achieve the highest annual electricity yield. A parabolic pattern with maximum output at midday is characteristic of this orientation. As module technology has progressed towards bifaciality, new possibilities for electricity generation have emerged. With east-west orientation and a vertical mounting, two yield peaks are generated in the morning and evening hours, which produce similarly high yearly energy yields as inclined south-facing power plants. Measured from agri photovoltaic systems even suggests an increase in yearly electricity yield in practice.

In this publication, different proportions of vertical east-west and inclined south systems are included in an energy system model 2030 for Germany and the effect of the former is analyzed. Software tools used were PVGIS to generate PV power generation profiles and EnergyPLAN for energy system modelling. It becomes clear that the vertical mounting of bifacial solar modules in east-west facing direction as a complement to south facing power plants can offer an additional value for stabilizing the electricity grid. This additional value is due in particular to the complementary electricity generation patterns for daytime balancing, because the usual midday peak of southern installations is shifted towards the morning and evening hours. In this exemplary sustainable German energy system model for 2030 (80% CO_2 reduction compared to 1990), 10.2 $MtCO_2$/a can be saved without electricity storage by orienting 80% of the installed photovoltaic capacity (equivalent to 280 GW_p) vertically towards the east-west. If electricity storage of 1 TW charging and discharging power and 1 TWh capacity is integrated into the energy system model, the effect is reduced to CO_2 savings of up to 2.1 Mt/a with 70% vertical east-west and 30% inclined south facing modules. The reasons for the reduced emissions are a change in the distribution of solar yields, better use of electricity storage and, as a result, reduced electricity generation demand from flexible, fossil gas-fired power plants. Lower savings through the large-scale integration of battery storage result from the fact that less southern PV electricity must be curtailed. The stabilizing effect of a vertical east-west oriented PV power generation is nevertheless visible, however, to a lesser extent.

A north-south orientation of vertical solar power plants provides higher electricity yields at low solar altitude in winter months. Therefore, it is assumed that vertical north-south elevations may have a potential for better seasonal balancing. According to the PVGIS software annual yield is 9% lower compared to the inclined south system. However, the collection of measurement data on electricity generation in practice is essential for further potential analysis.

The considered scenario of an 80% reduction of greenhouse gas emissions by 2030 is not sufficient in perspective. Further steps towards a share of 100% renewable energy in the electricity sector and climate neutrality must follow and be analyzed in further work regarding the integration of agri photovoltaic systems. The overall energy system optimization still has various deficits and requires further investigations. Furthermore, no cost estimates or tracking options were considered in this work and should therefore be investigated in subsequent work. Finally, while it might seem unrealistic for some to achieve a rate of 70% vertical power plants, even a lower rate has a beneficial impact. Vertical photovoltaic module orientation can be applied in bifacial open space power plants and also on facades of buildings or alongside traffic infrastructure. Consequently, the concept of vertical PV systems strongly increases space available for solar application and at the same time provides an approach for adapting energy production to energy demand.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2022.100083.

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