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Techno-economic analysis of photovoltaic battery system configuration and location☆

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HIGHLIGHTS

- A techno-economic analysis of battery system at two different locations in Almeria (Spain) and Lindenberg (Germany).
- The impact of changing orientation on SC, DA and LCoE in Germany is investigated.
- The study is done at two different tilt angles, near to the optimum values for the two locations at south orientation.
- The higher load profile is found to play a key role in increasing SC.
- A trade-off still has to be made between increasing self-consumption and achieving cost reduction for the coming 20 years.

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ABSTRACT

The techno-economic analysis investigates first the impact of tilt angle and orientation on the production profile of a rooftop solar generator and the related performance of a photovoltaic battery storage system for single family houses at a specific location in Germany. Then, a technical comparison to a different location in Almeria in Spain is performed.

The calculations are model-based and take into consideration the consumer load profile, technical and economic photovoltaic battery storage system parameters as well as the framework of regulations for the case of Germany. The parameters "share of self-consumption", "degree of autarky", and "economic efficiency in terms of levelized cost of electricity" make up the focus of the modelling results. It is concluded that self-consumption and degree of autarky are strongly and inversely related. In terms of system design, a trade-off has to be made between aiming for high self-consumption and a high degree of autarky.

Key findings from the modelling results reveal that in Lindenberg in Germany, a south orientation gives the highest degree of autarky and the lowest levelized cost of electricity, but with the lowest share of self-consumption as well. For rooftops oriented towards east/west, an interesting possibility could be to split the total installed capacity (equally) between the two orientations. This makes it possible to benefit from the high self-consumption of the east orientation and the high degree of autarky of the west orientation. In general, it has to be considered that the optimum orientation strongly depends on the consumer load profile. The technical analysis shows that changing the location to Almeria increases degree of autarky and decreases share of self-consumption for south orientation with different magnitude that depends on the load profile. Finally, the results show opposite impacts that depend on orientation and location when switching from a tilt angle of 30° to 45°. For a south orientation in Almeria and Lindenberg, the degree of autarky is increased when approaching the optimum tilt angle, while for west and east orientations in Lindenberg self-consumption increases.

1. Introduction

The strong growth in the number of photovoltaic (PV) installations worldwide since 2010 [1] has shown that this technology has taken a major step towards positioning itself as a good alternative to conventional energy resources in order to lower CO_2 emissions and meet the increasing global energy demand. On the other hand, the intermittent nature of this resource raises the problem of how to balance the supply and demand of electricity. In the case of small-scale rooftop PV systems for private households, battery energy storage systems (BESS) offer the opportunity to match the PV energy supply with the respective consumer load profile and thus significantly increase the share of self-

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consumption (SC) and the degree of autarky (DA). These two parameters make it possible to assess the congruence of the PV generation profile and the electricity demand profile, as SC is defined by the ratio of PV directly used to the total amount of PV generated, and DA is defined as a ratio of PV directly used to the total consumption by the household [2].

The self-consumption of locally produced electricity is gaining popularity due to falling system prices for PV [3] and BESS [4,5], on the one hand, and increasing end-consumer electricity prices [6,7], on the other. If price trends continue, costs for generating electricity via PV BESS can be expected to reach grid parity in several countries in the near future.

The design and the optimization of PV BESS have been the subject of research in different studies [2,8–21]. For instance, the economic study [21] investigates the impact of adding BESS on cost-effectiveness for two different battery systems (Vanadium redox flow and Lithium-ion batteries) using irradiance data from one location at Johannesburg and a load profile of the national load data of Kenya. Pb-acid and Li-ion batteries were compared as well under three different retail tariff systems in combination with PV generation for a single home in Switzerland [18].

A cost optimization was also made under Portuguese regulations to investigate the cost reduction required to enhance self-consumption [19]. A same approach was applied using real measurement data of solar radiation in Aachen Germany and load profile in commercial application to investigate the influence of different PV system size, PV system cost and interest rates [20].

Most of the existing techno-economics studies investigate in common the impact of battery capacity and installed PV power on the performance (SC) and the impact of component cost and tariffs on reduction of PV BESS systems costs. The current study offers a different perspective of analysing the performance and the cost of PV BESS system by looking at the parameters that impact directly the PV output power.

In this paper the impact of tilt angle and orientation on the production profile of a rooftop solar generator and the related performance of a PV BESS for single family houses is analysed firstly for a specific location (Lindenberg, Germany, Fig. 1), focusing on the parameters SC and DA (Fig. 1). The impact of these two parameters on the PV power output has been the subject of different studies [22,23] promoting the south orientation as the optimal configuration independently from the location. Concerning the tilt angle, the location plays a key role for finding the optimal configuration. As an example, at Incheon Korea the optimal south tilt angle is found to be 60° [22] which is different from the optimal configuration used in the study at Lindenberg. Different seasons impact as well the optimal tilt angle. Changing the tilt angle of the photovoltaic array in the cold and hot season improves considerably the performance and uniformity of the power output of the photovoltaic array [23].

Based on the analysis of tilt angle and orientation, a techno-economic calculation is supplemented by an investigation of the cost-effectiveness in terms of levelized cost of electricity (LCoE).

To investigate the impact of consumption and changing location on SC and DA, a technical comparison with a different location in southern Europe (Almeria, Spain) is performed at south orientation for different tilt angles and different load profiles (Fig. 1).

2. Sustainable methodology and basis data

Two models were used to investigate the impact of the tilt angle, orientation and location on the performance of PV BESS. Section 2.1 presents a brief summary of the techno-economic model and Section 2.2 the PV output power model. Data and model input parameters are summarized in Section 2.3.

2.1. The BaPSi model

The BaPSi (Battery-Photovoltaic-Simulation) model [13] is a tool for the techno-economic analysis of battery-supported PV systems. With the simulation model it is possible either to calculate a fixed system configuration with defined PV system size and battery capacity, or to conduct an iterative parameter variation to determine the cost-optimized combination of the PV system size (power rating) and the nominal capacity of the battery. The battery is integrated into the energy balance of a household considering PV production and household consumption. Here, the direct self-consumption of PV electricity (simultaneous consumption and generation of PV electricity without storage) is always prioritized over storage in the battery and feeding into the electric grid. The energy balance is calculated for every time step. The internal resolution of the model depends on the resolution of the input data time series. The required input parameters for the model calculation are economic parameters, household load profile, and PV BESS data including technical parameters and costs (see Section 2.3). Output parameters are the cost-optimal system configuration with and without battery as well as technical parameters including SC and DA. The calculation of total costs for electricity supply is based on the net present value approach by considering all costs and revenues during the operation of the system to meet complete household electricity demand. Major cost components are the costs of electricity supply from the grid – to meet the remaining electricity demand after SC from the PV BESS – the investment costs for the PV BESS, and costs of system operation and maintenance. Revenues are generated from the feed-in of surplus electricity generation, which is compensated by a guaranteed feed-in tariff. For the cost calculation, the current regulatory framework and the taxation system in Germany are considered according to [15]. The resulting total costs are therefore costs after income tax. The optimization goal is the minimization of total costs of electricity supply. As a benchmark for PV BESS it is possible to consider either grid supply of electricity only, or grid supply in combination with a PV system (without battery). LCoEs are calculated by dividing the total costs of electricity supply by the total household electricity demand in the simulation period considered.

The economic analysis was limited to the case of Germany, as changing the location to Almeria is Spain will change the electricity prices and different support schemes (Feed-In-Tariffs and battery implementation support).

2.2. The PV output power model

PV output power depends on the time, location, tilt angle, and orientation of the PV module. For this reason, a model shown in Fig. 2 was developed to calculate the output power. This model is based on real horizontal irradiation data measured on site [24,25], and takes into account the different losses that occur during energy conversion from the module and the overall system.

Firstly, the global irradiation for a given location is calculated as a sum of the direct, diffuse, and reflected irradiation on a tilted surface of angle β at an arbitrary angle orientation α (Eq. (1)).

$$G_{\alpha,\beta} = B_{\alpha,\beta} + D_{\alpha,\beta} + R_{\alpha,\beta} \tag{1}$$

Direct beam $B_{\alpha,\beta}$ is expressed as a product of sun position incidence $cos\theta_s$ and the measured data of the direct beam on a horizontal surface B_n (Eq. (2)).

$$B_{\alpha,\beta} = B_n * \cos\theta_S \tag{2}$$

The sun position is the angle of incident rays (Eq. (3)) at a given position to the normal of a tilted surface at arbitrary orientation calculated from θ_z, Ψ_s,β, and α, respectively, sun zenith and azimuth angles, and surface tilt and orientations angles.

$$\cos\theta_s = \cos\theta_z * \sin\beta * \cos(\alpha - \Psi_s) + \sin\theta_z * \cos\beta \tag{3}$$

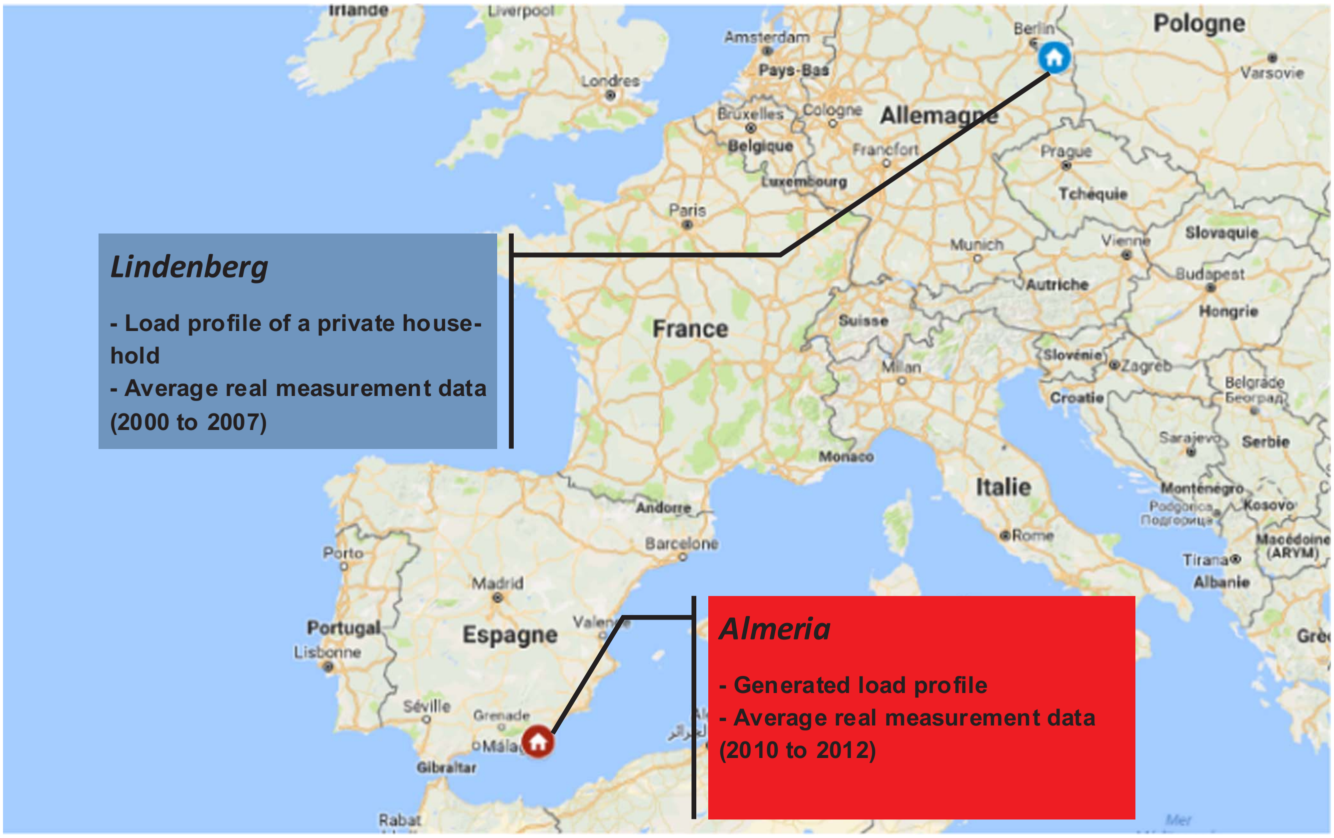

Fig. 1. Locations and load profiles of households studied.
Source: Own presentation using Google MyMaps (IEK-STE 2016).

The diffuse irradiation $D_{\alpha,\beta}$ is expressed as a product of diffuse irradiance transposition factor R_d described by the Klucher model [26] and the measured data of diffuse irradiation on a horizontal surface D_h (Eq. (4)).

$$D_{\alpha,\beta} = R_d * D_h \tag{4}$$

Finally, the reflected irradiation $R_{\alpha,\beta}$ is calculated from the measured data of global irradiation G_h on a horizontal surface and uses the foreground's albedo ρ, which depends on the type of the surface and ranges from 0 to 1. For the chosen location (both Lindenberg and Almeria), it was taken as equal to 0.2 [27] (Eq. (5)).

$$R_{\alpha,\beta} = \frac{1}{2}(1-\cos\beta) * \rho * G_h \tag{5}$$

The system output power is calculated by multiplying the installed PV capacity by the final energy yield Y_F. Where Y_F is the ratio of PV output power P_{PV} and the nominal power of the module under standard irradiance conditions $P_{m,ref}$, P_{PV} takes into account the inverter specifications (Enphase Energy C250-72-2LN-2 [28]), the module specifications (Suntech STP255S-20/Wd [28]), and all the system losses (Eq. (6) and Fig. 2).

$$Y_F = \frac{P_{PV}}{P_{m,ref}} = k_T * k_c * k_s * \frac{G_t}{G_{ref}} \tag{6}$$

Losses during energy conversion are accounted for via correction factors. k_T is the correction factor due to thermal losses, k_s is that for inverter losses, and k_c represents other losses [28].

Optic losses are implicitly included in the ratio between G_t, the global irradiance transmitted through the cover of a PV module, and $G_{\alpha,\beta}$, the global irradiation on a tilted surface of angle β at arbitrary angle orientation α. In addition, G_{ref} is the irradiance at standard conditions (1000 W/m^2) [28].

The model was used to calculate the output power of a PV installation in Lindenberg in eastern Germany and Almeria at the Mediterranean coast in southern Spain. For the first location, the measured time series of solar irradiation and meteorological data is available in one-minute resolution for the years 2000 to 2007 [24] and is used as an input data series for the model. For the second location only data from 2010 to 2012 [24,25] are used with one minute resolution as well.

2.3. Input parameters

The input parameters of the BaPSi model can be divided into four categories: "Consumer", "PV system", "Battery system", and "Economic parameters".

The consumer load profile used for the calculations in the case of Lindenberg in Germany is a measured load profile of a private household, originally available in one-second resolution. For the model calculations, a typical load profile from a published dataset [29] has been selected with total annual electricity consumption of 5010 kWh/a. For reasons of data protection, additional information about the profile (e.g. household type) is not available. However, with respect to total annual electricity consumption, it can be assumed that the selected profile represents a four-person household. In order to adjust the temporal resolution of the load profile to the PV production profile, it was averaged and converted to a temporal resolution of one minute.

For Almeria in Spain, a synthetic load profile generated by a simulation tool of the Technical University Chemnitz [28] has been selected with total annual electricity consumption of 5200 kWh/a. The profile has been calculated based on a single family house with four persons (2 adults, 2 children) under consideration of electric air conditioning for cooling.

The PV electricity generation profiles were calculated with the PV output power model. The resulting solar yield varies depending on the

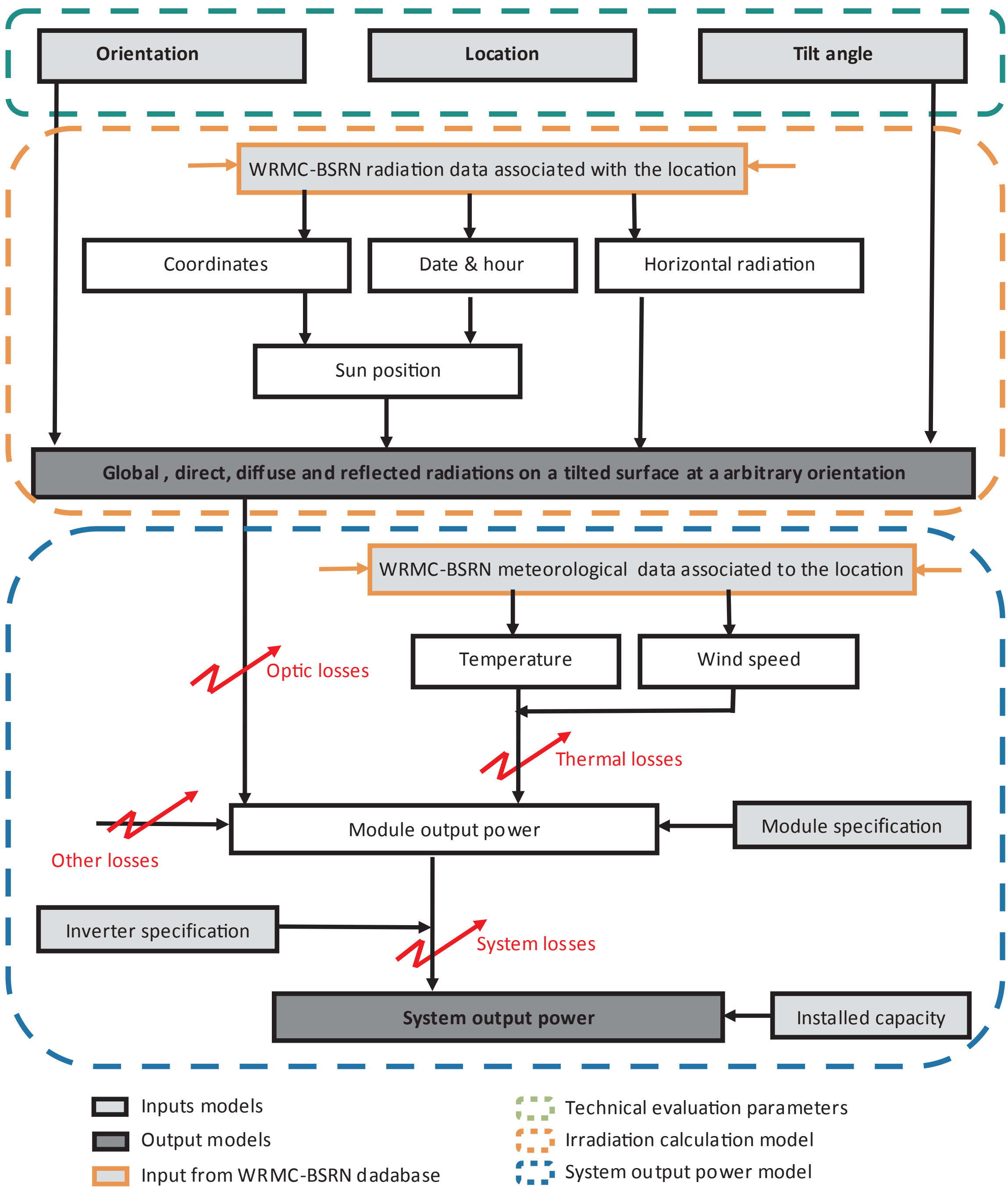

Fig. 2. Structure of the PV output power model.
Source: Own presentation using Microsoft Publisher 2016 (IEK-STE 2016).

tilt angle and orientation. The averaged PV electricity generation profile of the years 2000 to 2007 and 2010 to 2012 are used as input dataset of the BaPSi model for Germany and Spain respectively.

The BaPSi model supports lead-acid and lithium-ion battery systems. In the following calculations only lithium-ion systems are considered. The specific investment for the battery system of 400 €/kWh (without VAT) is rather optimistic given the current price level of 1100–2100 €/kWh (excluding VAT) in Germany for lithium-ion systems [5]. Nevertheless, driven by decreasing cell and module prices [30], there have also been significant price reductions at the system level for PV BESS of approx. 18%/a from 2013 to 2015 [5]. It can therefore be expected that the considered price level will be reached in the near future. In Germany, the installation of PV BESS is supported by state funding, which includes a discounted credit rate and a grant on investment [31].

The PV BESS commissioning date for system modelling is assumed to be 1 July 2016. According to the feed-in tariff system in Germany, it is assumed that the operation period of the system is equal to the feed-in tariff payment period. Under the current regulation, this period is 20 years plus the rest of the year in which the system was commissioned [32].

The electricity price (28.7 ct/kWh) considered represents the average price level for private households in Germany in 2016 (incl. taxes and levies) [33]. The electricity price increase is expected to slow down significantly from more than 5%/a in the period from 2000 to 2013 [33] to 2%/a as an average value during the next 20 years. Table 1 provides an overview of all parameters used in the model calculations.

Table 1
Overview of considered input parameters..
Source: Own presentation (IEK-STE 2016)

PV system		Battery system	
Module degradation	0.5%/a	Battery degradation	1%/a
Specific investment[a]	1240 €/kWp	Specific investment[a]	400 €/kWh
Operation costs[b]	1%/a	Depth of Discharge	80%
Maintenance costs	10 €/(kWp*a)	Roundtrip efficiency	90%
Economic parameters[c]			
Feed-in-Tariff			12.31 ct/kWh
Electricity price			28.7 ct/kWh
Electricity price increase			2%/a
Interest rate			2.5%/a

[a] Excluding VAT.
[b] As a percentage of investment in the PV system.
[c] Economic parameters for Germany.

3. Model calculations

In the first step, a fixed system configuration is considered in the calculations consisting of a 6.12 kWp PV system with a 5 kWh Li-Ion BESS. The installed PV size was derived from a database evaluation for renewable energy installations in Germany [34]. According to this database, the average size per PV installation is 6.2 kWp for the residential segment of PV installations up to 10 kWp. Although average PV size on private households in Spain might differ, the size was kept constant in Almeria to make the results comparable.

Due to the rated power of the PV module (Suntech STP255S-20/Wd), which is 255 Wp, the PV size considered for the model calculations was set to 6.12 kWp, which corresponds to the installation of 24 modules. The size of the battery system (5 kWh) is typical for households with an electricity consumption of approx. 5000 kWh and a PV system of 6–7 kWp, according to a statistical evaluation of installed PV BESS [5]. In a second step, the BaPSi model is operated in optimization mode to determine the cost-optimal system configuration in terms of PV size and battery storage capacity. For both cases, the model calculations

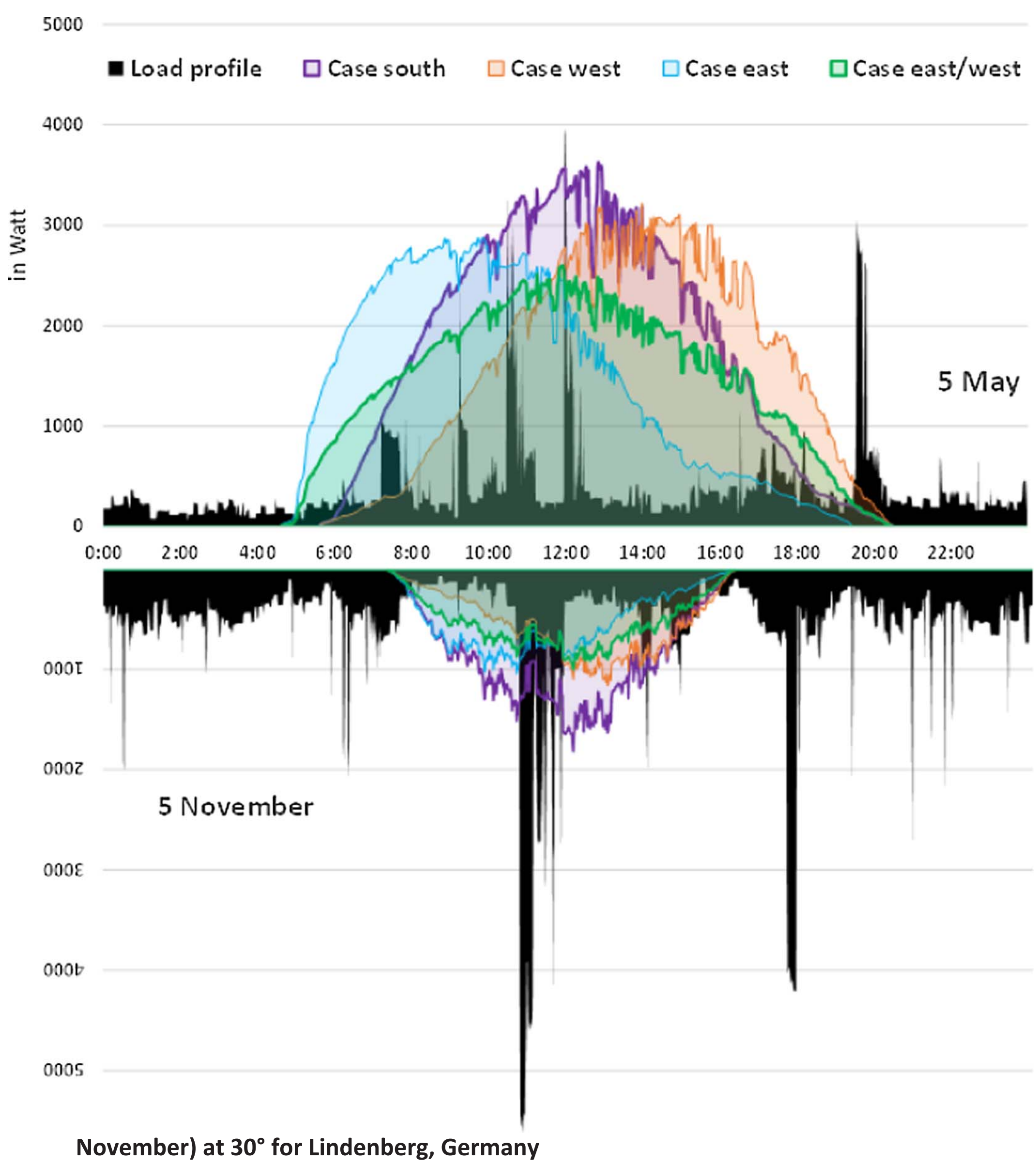

Fig. 3. Electricity production and consumption during summer (5 May) and during winter (5 November) at 30° for Lindenberg, Germany.
Source: Own calculation using Matlab R2016b/Microsoft Excel 2016 (IEK-STE 2016).

Table 2
Results of model calculations for a PV size of 6.12 kWp at 30° and 45° tilt angle, with and without storage of 5 kWh in Lindenberg, Germany.
Source: Own calculation using Matlab R2016b/Microsoft Excel 2016 (IEK-STE 2016).

Orientation		Case south		Case east		Case west		Case east/west	
Tilt angle		30°	45°	30°	45°	30°	45°	30°	45°
Load		5 010.0 kWh/a							
PV generated (kWh)		5 471.0	5 626.7	4 420.9	4 260.1	4 860.6	4831.1	4 640.7	4 545.6
Capacity	PV size	6.12 kWp							
	BESS capacity	5 kWh							
SC	PV	33.2 %	33.6 %	37.2 %	39.2 %	36.5 %	37.0 %	38.9 %	39.5 %
	PV+BESS	55.1 %	55.3 %	60.8 %	64.2 %	57.8 %	59.0 %	61.4 %	62.9 %
DA	PV	36.7 %	37.3 %	32.8 %	33.4 %	35.4 %	35.7 %	36.0 %	35.8 %
	PV+BESS	60.2 %	62.1 %	53.7 %	54.6 %	56.1 %	56.9 %	56.8 %	57.1 %
LCoE (ct/kWh)	No PV	26.63							
	PV	23.17	22.92	24.88	25.05	24.08	24.10	24.32	24.46
	PV+BESS	23.28	22.91	25.20	25.33	24.41	24.38	24.64	24.74

are carried out for two tilt angles associated with three different orientations.

According to [34], the majority of residential houses in Germany were built with a tilted roof angle between 40° and 45°. According to the PVGIS model [29] the optimum angle for a PV installation for south orientation in Lindenberg is found equal to 44°. Furthermore, a trend for switching to the 30° inclination in order to save space inside the building is projected. Based on these observations, 45° and 30° are kept for investigating the tilt angle effects.

For the orientation effect, the north orientation was not simulated as it gives the lowest annual solar yield, so, only four combinations of modules orientations were analyzed for Lindenberg:

- Case south, corresponding to 24 modules facing south.
- Case east, corresponding to 24 modules facing east.
- Case west, corresponding to 24 modules facing west.
- Case east/west, corresponding to 12 modules facing east, and 12 others facing west

Finally, the effect of changing the location will be investigated by choosing another location in Almeria, Spain. This place has the particularity to have houses with flat roofs only, therefore the house owners (potential users of PV BESS systems) will go for the highest irradiation configuration, which implies south orientation and optimum tilt angle for this orientation.

According to the PVGIS model [29], the optimum tilt angle for south orientation in Almeria is equal to 32°, in order to allow the comparison to Lindenberg, both cases of 30° and 45° are simulated.

The user profile is found to be a key parameter and influences SC and DA. To investigate the effect of changing location alone, this parameter has to be held constant by considering a theoretical load profile in Almeria without cooling similar to the case in Lindenberg. So SC and DA with and without BESS will be calculated for a location in Almeria at south orientation for two cases:

- Case with cooling, corresponding to a load profile in Almeria with air conditioning with total annual electricity consumption of 5201 kWh/a.
- Case without cooling, corresponding to a load profile in Lindenberg with total annual electricity consumption of 5010 kWh/a.

4. Results

4.1. Orientation and tilt angle effect at fixed location

Fig. 3 shows the consumer load profile and the PV production profiles for different orientations during two days of the year – one during summer (5 May) and one during winter (5 November).

On average, the load profile represents three main periods of consumption during the day: one in the morning, one peak at midday, and one that starts at the end of the afternoon and continues into the early part of the night. Depending on the orientation, the PV production peak changes according to the movement of the sun. The south orientation has the most important production peak at midday, followed by the west orientation with a peak in the afternoon and the east orientation with a peak in the morning. Finally, the production in the east/west orientation is more equally distributed over the course of the day.

In summer, placing modules only in the east allows to cover the main consumption in the morning and a part of the midday peak. However, the main power produced early in the morning is fed into the grid. The same applies for the west orientation as the main afternoon production is not directly consumed; this time only part of the midday peak, the afternoon, and a small part of night consumption can be covered. Placing modules towards the east/west on a rooftop makes it possible to simultaneously cover the major midday peak, the morning consumption, and to reduce the level of electricity purchased at night in summer time. It also has the advantage of increasing SC, incorporating overall lower electricity production. The south orientation makes it possible to cover more demand at midday, but does not cover the early morning or the end of the afternoon demand. Moreover, energy not directly consumed is increased, compared to east/west orientations, which decreases SC.

In winter, the south orientation is more interesting with the highest overall production and higher direct SC. As the days are too short to cover demand by PV production during morning and evening times, it is therefore better to target midday consumption.

Table 2 shows the values of SC, DA, and LCoE for different orientations at 30° and 45° tilt angles, and a fixed PV and BESS system configuration (in green, the highest values of PV generation, SC and DA, and the lowest LCoE; the opposite is indicated in red).

Rooftops oriented towards the south generate 610–796 kWh more PV power than the maximum PV generation of east and west orientations. The increase in PV generation increases the amount of PV not directly consumed, and consequently reduces SC. This explains the fact that the south orientation has the lowest SC.

For the other orientations, SC is increased significantly due to lower PV generation. Especially for east/west orientation PV generation and electricity demand are matched to a higher extent.

Another way to positively impact the SC is to add a BESS to the PV system. For this system combination the SC increase by 64% for the south orientation and by 58% for the east/west orientation.

In contrast to SC, DA benefits from high PV generation. This explains why the south orientation, which has the highest PV generation, has the highest DA (36.7%).

For the LCoE, cost-effectiveness is achieved with higher PV feed-in into the grid, which is compensated by a feed-in tariff. Overall, the south orientation has the lowest LCoE (23.17 ct/kWh) and the east orientation the highest one (24.88 ct/kWh) – both at a tilted angle of 30°.

Placing the same PV size on rooftops facing east/west does not enable to lower LCoE compared to west orientation, even with higher DA. This suggests that PV generation has a strong effect on LCoE.

Adding a fixed storage capacity of 5 kWh is not cost-effective – except for the south orientation with a tilt angle of 45°. This is due to the fact that the battery capacity was dimensioned taking into account the load profile, and remained constant to allow comparison of different tilt angles and orientations. In fact, the optimum BESS size that yields the lowest LCoE for both 30° and 45° tilt angles is 3.5 kWh for the south orientation and 0.5 kWh for other combinations of east and west orientations.

As the optimum angle for south orientation is close to 45°, increasing the tilt angle from 30° to 45° increases PV generation and DA for PV BESS by 2% without any notable effect on SC, but reduced LCoE by 0.36 ct/kWh (Table 2).

For the east/west orientation, switching from 30° to 45° increases SC for PV BESS by 1.6% without any notable effect on DA. However, this increases LCoE by 0.1 ct/kWh due to the lower PV generation (Table 2).

4.2. Load profile and location effects

To investigate the impact of location and consumer load profile on PV production and consumption, the yield of modules placed in Almeria in south of Spain is compared to the case of Lindenberg in Germany with a fixed tilt angle of 30° and a fixed orientation towards the south.

Fig. 4 shows the consumer daily load profile, the daily PV production and the monthly PV directly consumed during the year, for the two locations at 30° and south orientation.

In general, changing location changes the amount of incoming irradiation and meteorological conditions which impacts on the PV production. The load profile changes as well depending on the location. In the case of Almeria, located on the southern Mediterranean coast, summer is hotter and more consumption is needed due to the use of electric air conditioning for cooling during summer time. In the case of Lindenberg, located at north east of Germany, winter is harder and the use of cooling is not needed, although electrical consumption is usually higher except in the hottest months of the year (June, July and August).

In winter time, cloud covered days and less irradiation in Lindenberg results in less PV production compared to Almeria. This difference is balanced by more demand in Lindenberg, which explains that PV directly consumed is as important as in Almeria (see Fig. 4).

During summer, the PV production between the two locations is almost similar and this is due to two reasons. Firstly, a location on the southern Mediterranean coast shows better irradiation compared to Lindenberg. Secondly, the high temperatures during midday in Almeria impacts on the panel efficiency due to thermal losses which causes a drop in PV production compared to cooler locations like Lindenberg. Even with similar PV production, PV directly consumed in June, July and August in Almeria is more than doubled compared to Lindenberg. This can only be explained by the fact that electrical cooling during the day benefits for self-consumption.

It seems therefore, that the load profile plays a key role in PV consumption, and as a consequence, will impact by definition on DA and SC as well. Consequently, to investigate the impact of changing location on technical parameters, the load profile is held constant and equal to the Lindenberg profile for both locations as it represents less seasonal variations.

Only the tilt angle was changed for both locations in addition to the ones representing the different optimum values for south orientation.

Table 3 shows the values of SC and DA for panels facing south in two different locations with a tilt angle of 30° and 45°, a fixed PV and BESS system configuration. In Almeria, results for both load profiles are summarized, but only the ones for the case without cooling is compared with Lindenberg (in green, the highest values of PV generation, SC and DA; the opposite is indicated in red).

Rooftops located in Almeria generate 2905–3111 kWh more PV power than those located in Lindenberg. When comparing the two locations at fixed load profile (without cooling), this increase of PV production in winter impact positively on DA independently of the user profile, as DA increases in both cases. The increasing of DA has a negative impact on SC as seen for the comparison of different orientations.

In case of a user profile with cooling, the DA increases by 11% to 12.4% furthermore with and without BESS respectively. This suggests that PV production directly consumed and consumption match to a larger extent in this case due to higher electric air conditioning demand during the hottest days of the year. This difference in consumption impacts SC as well.

When using air conditioning during the day at the hottest months, more PV energy is directly consumed resulting in higher SC. This explains why SC in the case with cooling is 8.2% to 8.8% higher compared to SC in the case without cooling.

The relationship between the tilt angle and solar yield is seen to move in opposite directions in the two locations. Increasing the tilt angle from 30° to 45° decreases the solar yield in Almeria while it increases in Lindenberg.

In fact, for Almeria, the optimum tilt angle for the south orientation is close to 32° instead of 45° in Lindenberg.

In Almeria, switching from 30° to 45° tilt angle decreases PV generation and slightly decreases DA for both PV with and without BESS and with and without cooling by only 0.5% maximum compared to 2% in Lindenberg. This can be explained by a little variation of solar yield in Almeria when switching the tilt angles. In fact, the difference between the PV generations of the two tilt angle is 40 kWh in Almeria compared to a difference of 156 kWh in Lindenberg. For both cases and locations, changing the tilt angle has no notable effect on SC as seen for south orientation.

5. Conclusion

The techno-economic analysis investigated first the impact of tilt angle and orientation on the production profile of a rooftop solar generator and the related performance of a photovoltaic battery storage system for single family houses at Lindenberg. The analysis showed that the south orientation with a 45° tilted angle is the optimum configuration in terms of LCoE. East/west orientation has a positive impact of smoothing electricity generation, although incorporating lower electricity generation and lower DA. For the merging trend of building houses with a 30° in Germany east/west orientations will increase PV generation, with a positive effect on LCoE.

An analysis of different locations was performed to investigate the impact of PV sites by comparing rooftop solar generator facing south in two different locations. The results shows that placing a solar generator in Almeria with south optimum tilted angle results in higher PV generation, increased DA and decreased SC compared to the same configuration in Lindenberg.

As suggested by the comparison between two different days of

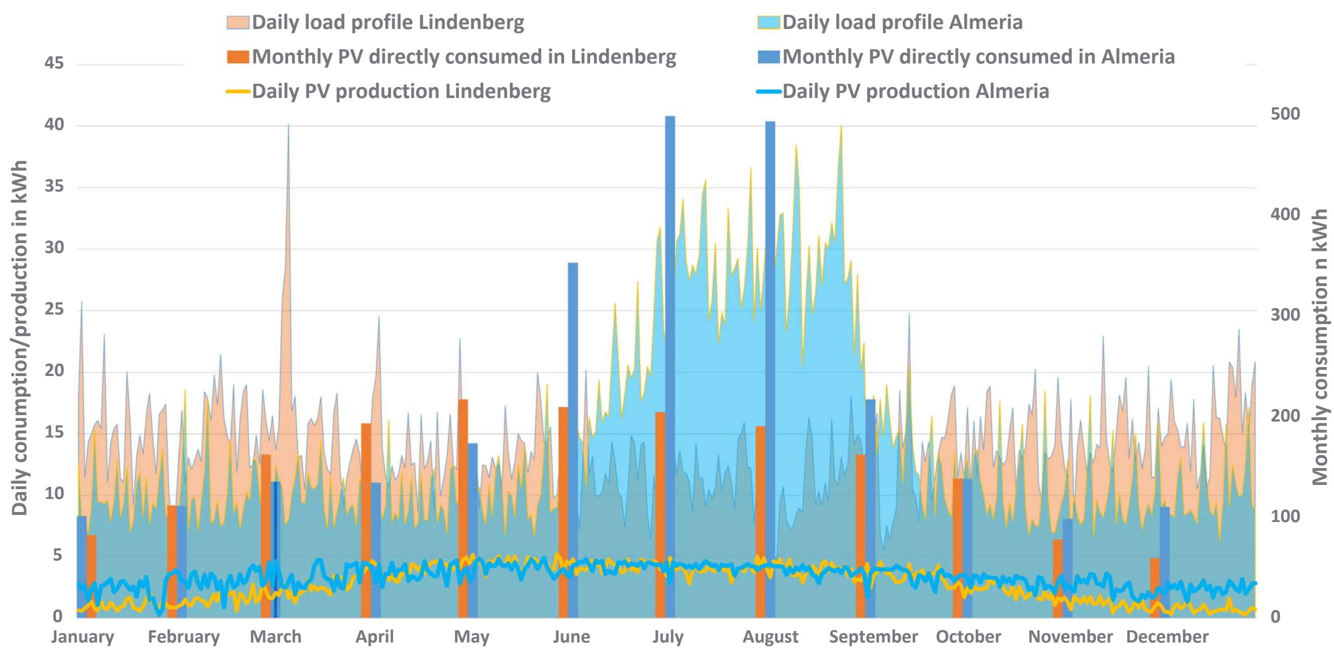

Fig. 4. Daily electricity production and consumption, and monthly PV directly consumed in Lindenberg and Almeria at 30° tilt angle and PV generator orientated to the south. Source: Own calculation using Matlab R2016b/Microsoft Excel 2016 (IEK-STE 2016).

Table 3
Results of model calculations for a PV size of 6.12 kWp at 30° and 45° tilt angle, with and without storage of 5 kWh in two different locations (Almeria in Spain and Lindenberg in Germany for different load profiles).
Source: Own calculation using Matlab R2016b/Microsoft Excel 2016 IEK-STE 2016.

Orientation		Case south					
Location		Almeria, Spain				Lindenberg	
Load profile		Case with cooling		Case without cooling			
Tilt angle		30°	45°	30°	45°	30°	45°
PV generated (kWh)		8 581.9	8 531.5	8 581.9	8 531.5	5 471.0	5 626.7
Capacity	PV size	6.12 kWp					
	BESS capacity	5 kWh					
SC	PV	33.3 %	33.0 %	24.7 %	24.8 %	33.2 %	33.6 %
	PV+BESS	49.3 %	49.0 %	40.5 %	40.6 %	55.1 %	55.3 %
DA	PV	54.7 %	54.3 %	42.3 %	42.2 %	36.7 %	37.3 %
	PV+BESS	80.9 %	80.5 %	69.4 %	69.2 %	60.2 %	62.1 %

summer and winter for different locations, the results depend strongly on the consumer load profile. Households with different load profiles could therefore benefit from different orientations, for example households active in the morning or afternoon without a midday peak could benefit from east or west orientations.

Another parameter that strongly affects the results is the annual PV generation profile. In fact, to keep the results as generalized as possible, the average PV output power of 8 years and three years has been considered for Germany and Spain respectively. However, in Lindenberg, where cloudy days are more likely, the energy yield varies strongly from one year to the next.

In general, the results show that lower PV generation of other orientations compared to the optimum south orientation can partly be compensated by higher self-consumption due to a better congruence between the production and demand profile. In this context the development of smart home systems based on intelligent system integration of controllable loads has a high potential for load flexibilization to match supply and demand profiles. Overall, it can be ascertained, that despite slightly different performance, for all investigated combinations of orientation and tilt angle, the feasibility from a technical as well as from an end-consumer perspective has been proven in terms of the potential to lower LCoE due to PV BESS utilization in comparison to external grid supply only solutions.

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