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Effect of tariff arbitrage on photovoltaic battery economics using predictive control

Sandro Schopfer*[a], Verena Tiefenbeck[a], Elgar Fleisch[a], Thorsten Staake[b]

[a]*Chair of Information Management, ETH Zurich, CH*

[b]*Energy Efficient Systems Group, University of Bamberg, DE*

[*]*Corresponding author's mail: sandro.schopfer@ethz.ch*

Abstract

Following a sharp learning curve, photovoltaic systems with battery storage (PVB) installations are increasingly used in residential buildings to increase self-consumption and grid independence. The economics of such systems work best in sunny regions with high electricity tariffs. However, only a few are subject to constant and high electricity prices (e.g. most German utilities). Customers in countries like Switzerland or Italy face typically day and night tariffs where the amortization of a PVB system is more challenging: the operational cost of the PVB system is above the grid-supplied low tariff rate, but below the high tariff rate. This work investigates how differences in tariffs can be monetized by the end consumer by charging the battery during low tariff/off-peak hours and discharging it during high tariff/on-peak hours to reduce the consumer's electricity bill. A simulation study applied to over 4200 load profiles is presented that identifies feasible conditions for end consumers to apply arbitraging during days where the PVB system cannot adequately cover the demand. It is shown that consumers with large demand can significantly increase the systems economics. Consumers with small demand cannot benefit from arbitraging as they cannot recover the additional battery replacement cost. Consumers with intermediate demand may benefit from arbitraging if they consume a large portion of their demand during high tariff hours.

Keywords: Photovoltaic, battery, tariff arbitrage, load shifting, Monte-Carlo-simulation

1. Introduction

In recent years, battery storage systems that increase self-consumption of residential photovoltaic (PV) installations have received increased attention by end consumers. In 2013 more than 6000 PV battery (PVB) systems have been installed in Germany, with estimates that more than 100'000 storage systems could be sold annually in the residential market by 2018 [1]. Battery systems are known to provide multiple services. Besides providing grid independence, they can be used for load shifting, peak shaving, transmission and distribution grid upgrade deferral and provision of balancing energy for ancillary markets [2,3]. Each of these services can be combined with other services to generate value for specific actors in the electricity market. In this article, we focus on services at the end consumer level. PV battery systems can provide end users with a more economical and sustainable means of power supply and simultaneously provide grid independence to some degree [4].

In this article we show that this service can be combined with tariff arbitraging and identify conditions where tariff arbitraging can reduce the consumer's energy bill even further. Many of the above services that a battery may provide have potentially system-wide effects, yet from which the end consumer does not directly benefit. Consumer markets with dual tariff scheme, however, offer the potential for additional services that can be monetized directly the end consumer in addition to increasing self-consumption/grid independence. Dual tariff systems exist in many European markets like Italy or Switzerland; the lower rate typically applies during night-/ off-peak hours and the higher rate during day-/on-peak hours. Under such a binary tariff scheme, PVB systems may be more challenging to amortize (as opposed to single tariff markets as in Germany), because the operational cost of the PVB system is typically above the grid-supplied low tariff rate, but below the high tariff rate. However, the batteries of a PVB system may be used to overcome the price difference in a high and low tariff market. The strategy of utilizing price differences in tariffs to achieve cost savings is known as tariff arbitraging [5] and is physically realized by shifting loads from high tariff hours to low tariff hours using flexile loads or batteries. Therefore, the PV battery system can also be used to charge the battery from the grid during overnight low tariff periods, and discharging the battery to supply the household's electricity demand during times when electricity rates are high. This strategy will limit the fraction of energy bought during high tariff hours and can potentially increase the economics of currently rather expensive PVB systems, as it reduces the costs for grid supplied electricity at times when the sun doesn't shine or when batteries are discharged. However, load shifting causes increased battery cycling and may lead to early and frequent replacement costs of the battery. In this paper, the economic viability of PVB systems that perform tariff arbitraging using load shifting in addition to the provision local green energy using a large smart meter dataset.

2. Related work

Storage and is considered to be a major cornerstone of the widespread transition to sustainable electricity production, as it can be used to temporally store energy from intermittent renewable sources like wind and solar [6]. Because of the rather large initial costs of storage, many studies for service aggregation for stationary battery storage systems exist that seek to improve the overall economics of the system [5]. A case study presented by Graditi et al. [7] shows that the stand-alone application of arbitraging using load shifting is economically viable for medium and large electricity consumers. However, they stress that load shifting as a stand-alone service is for end consumers economically speaking not viable. A similar study that presented by Zheng et al. [8] that analysed load shifting for end consumers with different storage technologies confirms the previous study for Li-Ion technologies. The effect of tariff structures for PV coupled battery systems is studied by Parra & Patel [9]. They analyse the economic benefit of time shifting PV generated energy to times of higher tariffs proportional to hourly spot market prices without including grid sided charging. They conclude that constant single tariffs are still the most beneficial ones for the end user. Their study was limited to one load profile with a demand of 3.4 MWh. Many references exist that study algorithm design for flexible loads [2] using rule based or predictive controllers without incorporating life-cycle costs.

The contribution of this paper is the study of the combination of PVB self-consumption and tariff arbitraging by load shifting at days when the PVB system cannot completely cover the demand. This study builds up on previously published articles that exclude tariff arbitraging [4]. The ultimate goal of the study is to identify feasible conditions which increase the overall system economics. This is done by incorporating a large number of load profiles (4231), which allows to treat the load profile as a dependent variable with all its features like annual demand, fraction consumed during certain hours etc.

3. Methodology & data

3.1 System Architecture & operational logic

The analysis builds up on a simple system architecture that is most prominently used for new PVB installations for residential applications. The system consists of three major components, that is, the PV modules, a hybrid inverter and a battery as shown in (Fig. 1). The hybrid inverter combines the traditional photovoltaic DC-AC inverter and the battery inversion in one unit, making it very cost-effective and efficient at the same time. The operational logic of the system prioritizes direct demand coverage with available PV energy without utilizing the battery. In case of surplus PV production, the battery is charged with solar energy. The surplus energy must be exported to the grid if the batteries are fully charged and/or the solar production exceeds the demand. In addition to this operational mode we add another logic that facilitates load shifting to overcome high electricity rates. The logic is realized by charging the battery overnight with cheap electricity if the PVB system cannot sufficiently cover the demand during the day as illustrated on the right hand side of (Fig. 1). Note that at all only surplus energy from the PV modules directly is exported to the grid. It is evident that this operation mode is more frequently invoked during winter days as the demand exceeds the solar production. Note that this mode requires a predictive control element that builds up on load prediction of max. 24 hours ahead.

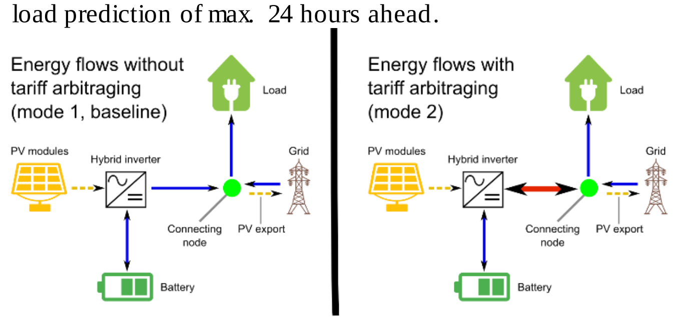

Fig. 1: System architecture and operational logic without (left) and with (right) tariff arbitraging.

3.2 Unit simulation

A simulation framework has been built to assess the economic viability of combined arbitraging and self-consumption.

Table 1: Listing of simulation inputs and outputs

Simulation Inputs	Simulation Output
- Load profiles	- Battery state of charge over time
- El. properties of PV modules	- Degree of self-sufficiency
- Installed PV capacity and battery capacity	- Net present values (NPV)
- Module orientation and tilt	- Return on investment
- Weather data (temp./sol. radiation)	- Levelized costs of el. (€/kWh)
- Investment costs/Tariffs	

Each of the system components is modeled by accounting for the most fundamental physical processes taking place in the respective component/device. A brief description is given in the following.

A) Photovoltaic modules

For given input data at standard testing conditions (STC) of a commercially available mono-crystalline module the current-voltage characteristic and its deviation from the STC is calculated for each time step in the simulation using so called translation equations [10]. The model is sensitive to ambient temperature and solar radiation.

B) Battery storage
Many battery models have been discussed in the literature [11]. Often they are very detailed and can determine voltage-current relations on the cell level. However, these are often restricted to a certain battery type or chemistry and require often complicated estimation of parameters. For the simple estimation of the economic viability of operation modes it is sufficient to model the battery using a simple energy balance with a given energy capacity.

C) Battery ageing
In this article, we do not restrict ourselves to certain battery type or chemistry but require certain requirements regarding the maximum charging cycle. The battery (for example Li-Ion) should be able to endure N_c=4000 cycles before its capacity fades to 80% of its initial capacity (theoretical end of life, EoL). It is assumed that the EoL can be determined by the total energy throughput, which can be obtained by cycling the battery N_c =4000 times. At the EoL, the battery is assumed to be replaced at the expense of the end consumer / owner of the installation. The maximum discharge depth (DoD) allowed to reach N_c =4000 is assumed to be 80%.

D) Inverter & battery discharging/charging losses
Inverter losses typically depend on the voltage level and the converted power. However, throughout this work, we assume that the inverter has an average efficiency of 95%. The battery discharging and charging efficiency are also assumed to be constant at 95%. The roundtrip efficiency of the battery is therefore 90.3% before the inverter and 81% after the inverter (AC-AC roundtrip efficiency), respectively.

3.2 Load data

Half-hourly load data from a large smart-meter pilot project in Ireland is used [12]. The dataset contains 4231 load profiles from participants all over Ireland collected during 75 weeks. Each load profile has been cropped to represent a full year with 17520 data points per load profile or consumer, respectively.

3.3 Weather data & pre-processing

Hourly solar radiation data (direct and diffuse radiation) and temperature data is used for the location of Zurich, Switzerland [13] for a typical meteorological year (TMY). The data is pre-processed to using solar azimuthal and elevation angles to project the radiation on any arbitrary oriented surface [10].

3.4 Cash-flow analysis

Once all physical state variables are known over time, the energy flows between all system components can be determined. The cost savings from the energy supplied from the PV modules or battery systems can be compared against the initial investment costs. This is done using the discounted cash-flow method which allows to derive a number of economic key performance factors such as net present value (NPV) or levelized cost of electricity (LCOE). The cash-flow model automatically determines the battery EoL and accounts for battery replacement costs. All economic calculations are performed by ignoring any upfront incentives like cash-bonus, subsidized feed-in tariffs or tax benefits.

4. Simulation study

4.1 Simulation set up

The simulation study aims to compare the two operational modes to identify feasible economic PVB systems:

- Mode 1 (baseline): Normal PVB operation without grid-sided battery charging for load shifting
- Mode 2: Applies overnight grid-sided battery charging whenever less or equal than 60% of the daily demand can be covered by the PVB system.

4.2 Monte-Carlo-simulation and probabilistic input parameters

In order to test the two operation modes under realistic conditions, we assign for each load profile/consumer in the dataset a fixed orientation and tilting angle using a given probability distribution. Thus each consumer is assumed to live in an independent house with defined orientation and tilting angle of the building according to the population. The seed for the draw of random numbers has been set to a constant, which ensures the reproducibility of this work. The probability distribution for the orientation is assumed to follow a normal distribution [14] with location parameter loc=μ=180°, and scale parameter scale=σ=50°. For the tilt angle of the PV module a Gompertz distribution is taken (loc=0, scale=12, shape=0.03) as shown in (Fig 2). Once the module orientation is assigned, a Monte-Carlo-simulation starts where randomized combinations of the installed PV capacity (kWp) and battery storage capacity (kWh) are simulated. Both the PV installed capacity and the battery storage capacity are drawn from a uniform probability distribution U(a,b) within the interval a≥0.26 kWp (1 module), b≤30 kWp and a>0 kWh and b≤20 kWh, respectively. In total, 256 annual simulations are executed per load profile with different PV power and battery capacity simulations. The simulation cannot be executed on normal personal computers due to large number of consumers in the dataset and the large number of repetitions per consumer (256). Code parallelization has been applied to split the problem up to multiple cores. The simulation code is currently executed using the super computer called ‘Brutus’ of ETH Zurich, which allows to utilize up to 128 CPUs in parallel.

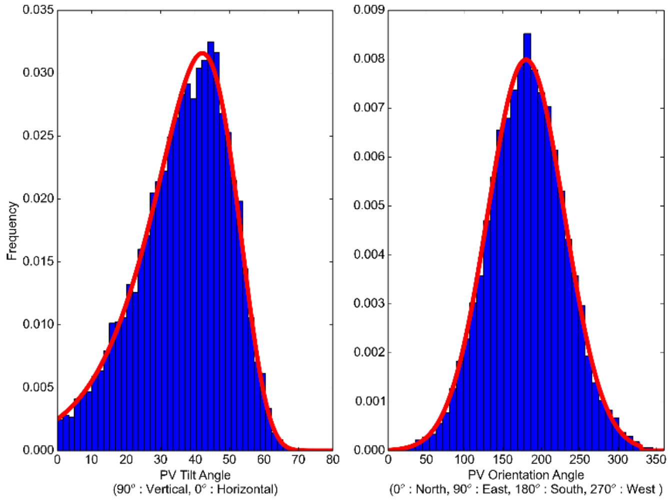

Fig. 2: Distributions for orientation and tilt angle

4.4 Deterministic input parameters

Table 2: Listing of deterministic input parameters

PV Module Properties	**Value**	**Comment / Reference**
Open circuit voltage / short circuit current	37.8V/9.8A	comm. available PV module
Max. power point voltage / current	30.7V/8.5 A	
Voltage / current temperature coefficient (at STC)	0.06 %/K / -0.31 %/K	
Module surface area	1.63 m²	
Battery properties		
Battery life cycles	4000	Current state of the art
Max. depth of discharge (DoD)	80%	
Inversion efficiencies		
Inverter efficiency	95%	
Charge/discharge efficiency	95%	
Economic parameters		
Specific plant costs incl. installation without battery	2000 €/kWp	[15]
Battery costs	500 €/kWh	[9], [16]
Replacement costs f. batteries	200 €/kWh	[16]
Discount factor	3% p.a.	
El. price escalation rate	2.5% p.a.	[17]
Incentives (Cash-Bonus)	0 €/kWp	
Tariffs (based on Zurich, Switzerland)		
High/low tariff rate (high tariff: 6am-10pm Mo-Sa)	0.24/0.16 €/kWh	
Feed-in tariff rate	0 €/kWh	

4.3 Aggregation of Simulation results

The Monte-Carlo-simulation generates for each output variable 256 cases per consumer, which must be aggregated in a meaningful way. One aggregation strategy consists in combining the installed PV power and the battery capacity that yield the highest NPV. An alternative aggregation strategy consists in combining the installed PV power and the battery capacity that achieves largest grid independence under the condition of a positive definite NPV. In this work we assume that customers install PVB systems with the motivation to achieve largest grid independence. Note that the self-sufficiency factor is calculated using mode 1 control logic. The effect of tariff arbitraging is computed using a post processing step with known daily self-sufficiency factors.

4.5 Ideal predictive controller for load shifting

As previously mentioned, load shifting with the goal of achieving tariff arbitraging must rely on dynamic load forecasting. In order to understand the upper limit of maximum savings that can be achieved using mode 2 operation, we assume that future load and solar production are perfectly known at any point in time for a max. duration of 24 hours ahead in time. Note that projections of demand and production within these time slots/windows can be achieved with high prediction accuracy as demand and production follow daily, weekly and seasonal patterns [18].

4.6 Savings on lifetime cost

The simulation results are presented using a savings parameter that compares the LCOE installation with the discounted costs for the case where no PV battery system has been installed (i.e. pure grid costs) abbreviated as $LCOE_0$. The savings in lifetime costs are thus defined as S_1=1-$LCOE_1/LCOE_0$ for the mode 1 (baseline operation) and S_2=1-$LCOE_2/LCOE_0$ for the mode 2 (tariff arbitrage operation). The savings parameter is greater than zero if the installation can be operated economically ($S>0$).

5. Results and discussions

The simulation results are shown in (Fig. 3), which illustrates the comparison between the baseline (mode 1, no load shifting) and the operation with load shifting. A total of 1025 (23%) out of the 4231 consumers in the dataset cannot reach a positive NPV for the baseline simulation (without tariff arbitrage through load shifting). The reason for this lies mainly in the small annual demand that does not allow to recover the large investment costs for the PVB installation. For the further analysis we restrict ourselves to the subset of the 3206 consumers that can reach a positive NPV in the baseline case. The comparison between the two operation modes within this subset is shown in (Fig. 3). Out of this subset, 1170 consumers that can reach a positive NPV in the baseline setting lose their profitability when switching to the tariff-arbitraging mode. As clearly observable in (Fig.3) consumers with less than 3500 kWh are undoubtedly in the region where they lose their profitability because the cost savings through arbitraging are not large enough to recover the additional replacement costs for the batteries. End consumers with a demand between 3500 and 5700 kWh have a second determinant, which is the fraction of energy consumed during high tariff hours as later seen in (Fig. 4).

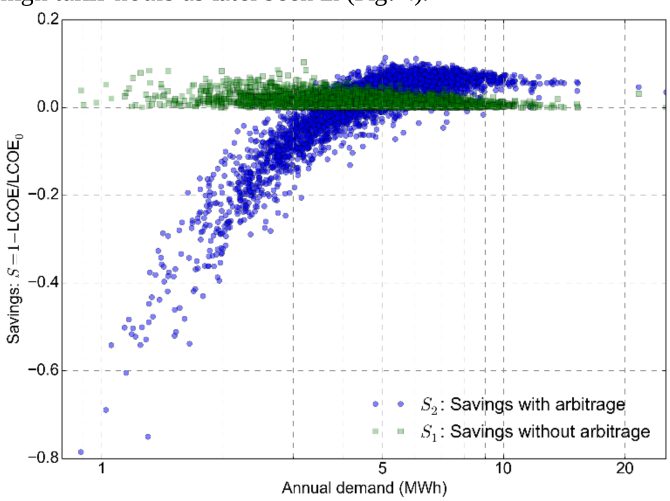

Fig. 3 Tariff arbitrage comparison with baseline

The majority of the consumers above 5700 kWh can reach savings above zero and are therefore suitable candidates for arbitraging with their PVB system. About 1833 (57%) consumers out of the 3206 consumers that can reach a positive NPV or $S_1>0$ in the baseline mode can achieve larger savings if they tariff arbitrage. Only 49 consumers (1.5%) that could not reach positive savings in the baseline, become profitable due to arbitraging. This is mainly because low demand consumers/profiles are generally speaking not good candidates neither for PVB systems, nor for arbitraging strategies, as they fail to amortize the large initial investment. The savings in the medium/high demand regime, however, can be considerably boosted using tariff arbitrage. A consumer with an annual demand of 6000 kWh with maximum savings around 4% in the baseline regime can reach 10% savings using tariff arbitrage.

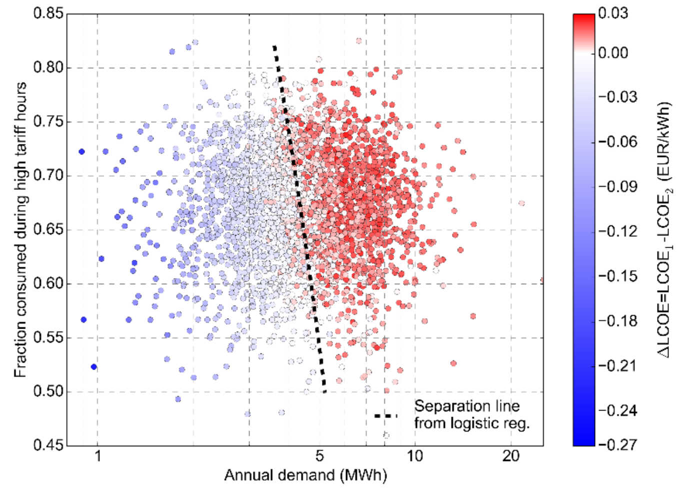

Fig. 4: Separation line for feasible tariff arbitraging

Consumers could also reinvest these savings in additional battery capacity (at expense of a lower but at least positive definite NPV) that guarantees larger grid independence. The second determinant for an economically feasible arbitrage condition is the demand during high tariff hours, as (Fig. 4) shows. In this scatter plot the annual demand and the fraction consumed during high tariff hours is used as the independent variable. The color of each consumer point indicates the difference ΔLCOE=LCOE$_1$-LCOE$_2$ between baseline and arbitraging mode. It is shown that arbitraging can reduce the LCOE by a maximum of 0.03 €/kWh. A separation line has been computed using a classification algorithm called logistic regression known from machine learning. The dataset has been split into an 80-20% training-testing dataset to train the algorithm which could achieve a classification accuracy of 89% for the present case. The decision line which separates the classes $\Delta LCOE \geq 0$ and $\Delta LCOE < 0$ shows clear dependence on the fraction consumed during high tariff hours. In fact, consumers with low annual consumption but elevated consumption during high tariff hours may still be good candidates for arbitraging. Conversely, consumers with similar demand but relatively low consumption during high tariff hours may lose profitability when tariff arbitraging. In the extreme case of low or even zero consumption during high tariff hours, arbitraging becomes indeed obsolete. With reference to (Fig. 3), the interval between [3500, 5700 kWh] corresponds to the region in (Fig. 4) where the classification decision (to achieve positive lifetime savings) is also determined by the fraction consumed during high tariff hours. This may lead to the conclusion that annual demand and fraction consumed during high tariff hours are two of the most important factors for feasible economic conditions to perform arbitraging.

6. Conclusions

A comprehensive simulation is presented that investigates whether it is economically feasible for PV battery systems owners to perform load shifting to benefit from low tariff prices in a dual-tariff market. The key assumption made to address this matter is a perfectly known future demand and solar production within a time window of max. 24 hours ahead. The results show that economically feasible conditions for arbitraging depend mainly on the annual demand and the fraction of energy that is consumed during high tariff hours. Consumers with high demand are generally speaking better candidates for PV battery systems and represent also the class which benefits most from arbitraging as they can recover the high investment costs easier. The fraction of energy consumed during high tariff hours is an important factor for consumers with a medium demand (3500 to 5700 kWh annually). Consumers at the lower end of this interval are only candidates for arbitraging if they consume most of their energy during high tariff hours. Other tariff structures with lower high tariff and lower high-low tariff spread between them are neither favourable conditions for PVB systems in general nor for tariff arbitraging enhancement. Inaccuracies of load prediction may result in smaller lifetime savings. However, neglected feed-in tariffs or other subsidies may considerably increase the lifetime savings. It is important to note that tariff arbitraging through load shifting can be designed to coincide with peak shaving, which can only be monetized in markets with peak load charges. The savings in such markets may be considerably higher as the peaks only occur during a short period of time. Tariff arbitraging can be also used to increase grid independence, because it allows to allocate the additional savings generated from arbitraging over the life-cycle into additional battery capacity which may be investigated in the future. A further field of study may be also the use of different charging modes that charge/discharge the battery using small power bursts [18] to lower the DoD and thereby making tariff arbitraging more economical.

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The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
Dr. Kumar is visiting faculty at Prince of Songkla University, Thailand. He have 16 years of research and teaching experience in the field of solar energy, drying and energy efficiency.

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