The Financial Analysis of Solar and Battery Power Purchase Agreements

Julia Altheimer[1], Stefan Trück[2], Rudi Zagst[3]

[1]University of Liechtenstein, [2]Macquarie University Sydney,

[3]Technical University of Munich

Abstract

Residential solar Photovoltaic (PV) systems have become one of the most popular distributed electricity source to provide clean and sustainable electricity for residents. In this context, solar Power Purchase Agreements (PPA) as a new financing mechanism enable third-party financing of residential solar PV systems, eliminating most financial and technical risks for residents. However, solar-generated electricity is intermittent, enforcing the need for Battery Energy Storage Systems (BESS) onsite PV systems (PV+BESS) for local electricity management and increased electricity self-consumption. The financing of residential PV+BESS under a solar-and-storage PPA is a nearly unexplored field in research. This study provides a framework for the design and structure of solar-and-storage PPAs. It implements a two-step techno-economic model to assess the financial viability of solar-and-storage PPAs both from a third-party and a resident (customer) perspective based on real-world electricity consumption and generation data of Australian households. We find that the residents can economically benefit considerably in terms of electricity bill savings from entering into a solar-and-storage PPA, whereby Time-of-Use tariff customers save more money than flat-rate customers. In contrast, financing a residential PV+BESS under a solar-and-storage PPA is an economically unbeneficial option for the third-party under current electricity tariff constellations in Australia. Nevertheless, the results suggest that BESSs increase electricity self-consumption of households and solar-and-storage PPAs may become a financially viable option in the future. Our results show that PPAs for small BESSs with policy support like subsidies on upfront investment costs of BESSs and high Feed-in Tariffs can even be viable in the current market environment.

Keywords: Power Purchase Agreements, Solar Photovoltaic Systems, Battery Energy Storage Systems,

1. Introduction

Climate change and the urgency to reduce CO2 emission, influences current policies of many countries around the world. Australia contributes to this challenge with its current target to reduce greenhouse gas emissions by 26-28% below 2005 levels by 2030 (Commonwealth of Australia, 2015). The transition and decarbonisation of its energy sector towards a cleaner system with an increased share of Renewable Energy Sources (RES) is a milestone towards this goal. However, the integration of RES into the existing electricity grid and the associated decommissioning of fossil fuel power plants will lead to a fundamental change in the energy sector design.

Due to Australia's high level of solar radiation, solar Photovoltaic (PV) systems offer a high potential for generating clean and sustainable electricity, alongside other renewables such as wind and hydropower (Geoscience Australia, 2021). Over the past decade, many policy incentive programs for financing PV systems, such as Feed-in-Tariffs (FiT) and rebates on PV system costs via small-scale technology certificates, innovative advances in PV technology, and falling module and investment costs have already led to impressive growth in PV system installations (Bahadori and Nwaoha, 2013; Best and Trück, 2020; Kumar Sahu, 2015; Macintosh and Wilkinson, 2011; Solangi et al., 2011; Sommerfeld et al., 2017). Particularly in recent years, the number of installations of PV systems in Australia has grown tremendously. In 2019, the technology ranked second with a current market penetration of almost 33% of total renewable energy generation, just behind wind power at 35.4% (Clean Energy Council, 2020a).

Even though Australia has one of the highest proportion of installed rooftop PV systems in the world (Elphick et al., 2020), the residential sector has been identified as still having a high untapped potential for electricity generation through the installation of rooftop PV systems (Maisch, 2019; Zander, 2020). Economic reasons dominate the motivation of residents to install PV. Zander (2020) identifies the reduction of electricity bills as the main motivation, followed by the avoidance of higher future electricity costs, the desire for energy autonomy and subsidies. Less decisively are environmental reasons such as personal footprint reduction and contribution to emission targets. However, most of the reasons that prevent residents from installing rooftop PV are also dominated by economic ones. Studies identified high upfront investment costs, high and uncertain maintenance costs, long payback periods and low return from FiT as major barriers to investing in PV (Balcombe et al., 2014; Palm, 2018; Zander, 2020). Besides, Zander (2020) also lists fear of system outages, unavailability when needed and lack of trust in solar panel companies.

Most of these barriers are related to the ownership and self-installation of rooftop solar PV systems, which is also associated with increased risks such as system outage. Over the last decade, there has been a growing interest in financing PV systems under Power Purchase Agreements (PPAs) to address the barriers that residents hinder to install PV systems on their property.

PPAs are financial mechanisms in the so-called Third-Party Ownership (TPO) business model that allow a third party to finance RES onsite the electricity consumer. In a TPO model, a third-party (electricity provider) operates as the investor of the RES, e.g. a rooftop PV system, from which the electricity consumer (customer) purchases and draws the green electricity. Both the third-party and the customer sign a PPA that regulates the supply of the green electricity at a predetermined price, usually lower than the retail price of the customer. PPAs reduce the risks of owning and self-installing RES on the customer's side by shifting the technical and financial risks of the installed RES to the third-party. The customer also benefits from savings on the electricity bill. The third-party benefits from the long-term contract by receiving revenue from the electricity payments of the customer and the FiTs secured for the duration of the contract.

In the literature, PPAs tend to be new financial instruments for funding RES via TPO (Mendicino et al., 2019). In Australia, PPAs are widely used to finance large-scale solar and wind projects, but less is known about their potential in the residential sector. A case study based on 300 households in Australia identifies residential solar PPAs as already economically beneficial for both the customer and third-party side (Best et al., 2019). However, the authors state that there is a high unrealised potential for the financial return of solar PPAs. On average, only 25% of the solar-generated electricity is sold to the customer. A higher share would increase the economic benefits of solar PPAs for both customers and third-parties.

A major downside of solar-generated electricity for private households is the temporal discrepancy with residential consumption patterns. Solar-generated electricity reaches its peak level around midday. Thus, it behaves oppositely to the average residential electricity consumption pattern, with peaks at off-peak times in the morning and evening. In grid-connected systems, the surplus solar-generated electricity that exceeds the residential electricity consumption at peak times is fed into the grid. During off-peak times, the residents draw the additional electricity they need from the grid.

Battery Energy Storage Systems (BESS) addresses the temporal mismatch between electricity consumption and generation by providing local electricity management. Typically, a residential BESS consists of a battery energy storage unit and an integrated inverter (Leadbetter and Swan, 2012). It is universally applicable, either as a small-scale onsite installation in the residential sector or as a large-scale installation in the commercial sector. A BESS combined with a PV system, called PV+BESS, enables load shifting from peak to off-peak times. A PV+BESS charges the surplus electricity from PV generation that exceeds the electricity consumption of the household during peak times and provides additional electricity to the residents during off-peak times, usually in the evening (Luthander et al., 2015). Thus, BESSs can serve as a buffer between the grid and the PV system to smooth fluctuations in electricity generation and increase the electricity consumption of the household of onsite generated green electricity. Despite the high potential of storage systems to improve grid stability, the market is still low (Miller and Carriveau, 2018).

One major disadvantage of BESSs for residential buildings is that adding a BESS to a PV system intensifies the financial barriers to installing a PV system. The BESS installation significantly increases the upfront investment costs of the overall system. Furthermore, Best et al. (2021) found that capital is an essential factor in the uptake of residential BESSs and that households under financial pressure are less likely to invest in residential BESSs. Furthermore, battery storage is a fairly new technology that poses technical and operational risks from the perspective of residents (Malhotra et al., 2016). The revenue from implementing BESS must exceed the additional installation and operating costs to become viable for residents.

BESSs can increase the residents' share of electricity consumption drawn from the locally solar-generated electricity by shifting the electricity generated at low demand periods to high demand periods (Hayat et al., 2019; Luthander et al., 2015; Roberts et al., 2019b). Thus, BESSs can increase the economic benefits of solar PPAs for both the customer and the third-party. Also, FiTs have been falling in recent years (Poruschi et al., 2018) and, thus, mitigate the revenue from solar-generated electricity fed into the grid. Therefore, low FiTs may reinforce the need for BESS installations onsite solar PV systems to increase the financial attractiveness of residential solar PV systems. In this context, Best and Trück (2020) identified low FiTs as conducive for actual uptake of BESSs. However, what we know from literature about the financial viability of PV+BESSs in the residential sector is primarily based on the assumption of the authors that the consumer owns the system (referred to as 'consumer-owned system') (Baek et al., 2020; Hoppmann et al., 2014; Young et al., 2018). However, Miller identified missing innovative financing methods and missing case studies demonstrating the financial viability of storage implementation as the main barriers to boosting the electricity storage industry (Miller and Carriveau, 2018).

In summary, both BESSs and TPO themselves have the potential to positively influence the financial viability of residential PV systems. Therefore, a comprehensive analysis of PPAs for PV systems only and PV+BESSs is crucial to uncover the full potential of financing RES via third-party ownership. But so far, the academic sector offers little guidance on how PV+BESSs can be funded through residential PPAs and whether this is a financially viable option for both customer and the third-party.

This study makes several contributions to the literature on the financial viability of solar PPAs in the residential sector. First, we develop an econometric framework for the analysis of residential solar PPAs with battery storage option, namely solar-and-storage PPAs. Second, we answer how and to what extent battery storage options affect the financial viability of residential solar PPAs. Or empirical analysis covers both solar and solar-and-storage PPAs, which allows us to measure the direct impact of BESS installation in addition to a residential PV system under PPAs.

The remainder of the paper is organized as follows: Section 2 provides a brief review of the related literature on third-party ownership models, solar PPAs, and the role of batteries energy storage systems in the residential sector. Section 3 outlines and the structure of solar-and-storage PPAs and develops the economic framework that is applied to analyse the financial viability of such TPO models. Section 4 describes the data, while Section 5 provides the key results of our empirical analysis. Finally, Section 6 concludes and provides some policy implications of our results as well as suggestions for future research.

2. Methodological Framework

2.1 The Design of Residential Solar-and-Storage PPAs

In the following, we define a solar-and-storage PPA as a financial instrument in a TPO business model to build a combined PV+BESS onsite for a customer and regulate the monetary cash flow between the third-party and the customer. Figure 1 illustrates the design of solar-and-storage PPAs, including all related parties, monetary cashflows and electricity flows.

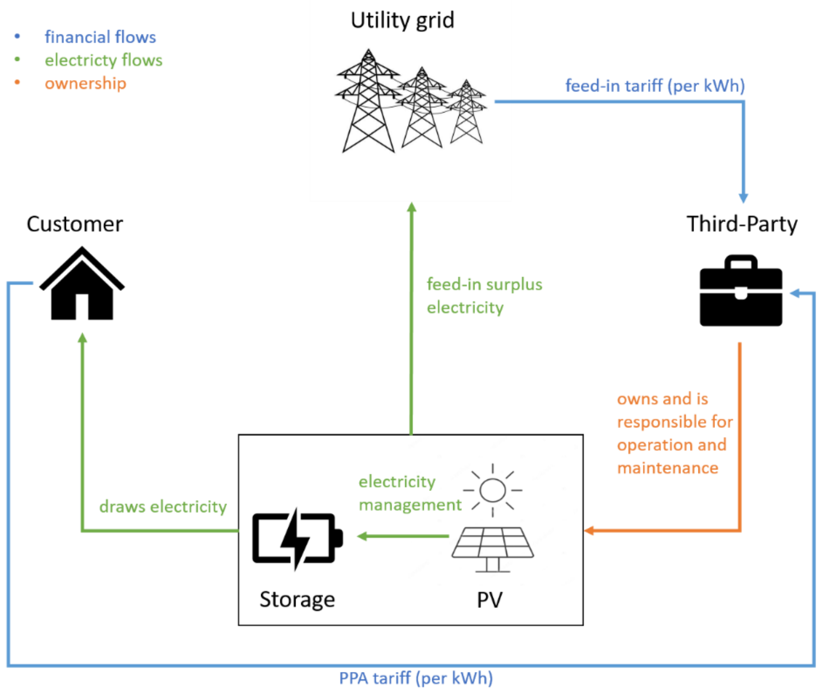

Figure 1 Illustration of solar-and-storage PPAs (Source: own presentation)

Equivalent to solar PPAs, the third-party owns the PV+BESS located onsite the customer and is responsible for technology selection, installation and operation and maintenance (O&M). Under a solar PPA, solar-generated electricity is first used to meet the demand of the customer. Thereafter, the excess solar-generated electricity is fed into the grid. Under a solar-and-storage PPA, the BESS enables local electricity management and the third-party, as the owner of the system, can decide on the control strategy[1]. The main application of BESS in solar-and-storage PPAs is to increase the electricity self-consumption and self-sufficiency. Therefore, we define the usage of the solar-generated electricity as follows:

First, the solar-generated electricity is supplied to the customer until the demand of the customer is covered. Then, the excess solar-generated electricity is used to charge the battery under consideration of battery technology characteristics. If there is still a surplus solar-generated electricity left, it is lastly fed into the grid. The customer retrieves the electricity stored in times of shortage periods of solar-generated electricity, e.g. in evening hours. When no electricity is provided by either the PV system or the BESS, the customer draws and purchases the electricity additionally from the grid to cover his/her total electricity consumption.

Cashflows are as follows: the customer pays the third-party a prefixed PPA tariff per kWh of electricity consumed either directly from the PV system or the electricity stored in the BESS. The payments hereby occur at the time of electricity usage, which is crucial for examining electricity bill savings under time-variant tariffs such as TOU tariffs. Furthermore, the third-party receives a FiT per kWh of electricity fed into the grid.

The contract duration, the PPA price structure, and the PV system size and BESS size are typical design parameters of PPAs. Like in solar PPAs (Cory et al., 2009), we assume the terms of the respective parameters as legally binding for both parties within the contract duration. Those have to

[1] The control strategy defines the rule of when to charge or discharge the BESS.

be carefully predetermined to ensure financial viability from both third-party and customer perspectives, outlined in the following.

The contract duration defines the period for which the PPA remains in force for both parties from the start date of the contract. 15 to 20 years are typical contract durations for solar PPAs (Thumann and Woodroof, 2009), whereas Davidson et al. (2015) found the main contract duration to be approximately 20 years. We suggest the same contract duration for residential solar-and-storage PPAs.

The PPA price structure defines the initial PPA tariff per kWh at which the customers agrees to purchase the electricity from the third-party in the start year of the PPA and its development over time. In general, the PPA tariff is competitive with the retail tariff, and in some contracts, a fixed discount on the retail tariff is assumed (Cory et al., 2009). As the installed RES supplies electricity directly to the customer, the third-party does not need to pay any network charges and can provide the electricity to a cheaper tariff. Furthermore, the spread between PPA tariff and retail tariff controls electricity bill savings on the customer side. Optionally, PPA contracts also include an annual fixed price escalation rate for the initial PPA tariff, reflecting the assumed target inflation rate of the following years (Cory et al., 2009). Usually, the price escalation rate amounts to 2% - 4% per year (Davidson et al., 2015; Speer, 2012). Supposing the same price structure for solar-and-storage PPAs, we expect higher electricity bill savings for the customers and higher revenue for the third-parties than under solar PPAs, as the BESS increases self-sufficiency and self-consumption.

The size of the PV system installed aims to cover as much of the electricity consumption of the customer as reasonably possible. Obviously, customers first have to estimate the available roof or ground area for the PV system to be located (Cory et al., 2009). From a financial perspective, the profit of the customer under a PPA increases the more solar-generated electricity is available. A higher PV system size increases self-sufficiency until the solar-generated electricity covers the total electricity demand and, consequently, the electricity bill savings of the customer. Therefore, we expect a larger PV system size to be more economically beneficial from a customer's perspective.

In contrast, the impact of a larger PV system on the third-party's financial viability of PPAs is not apparent. Firstly, a larger PV size installed results in higher investment costs the third-party has to afford. Secondly, as the PPA tariff generally exceeds the FiT, the third-party profits most from selling the electricity generated to the customer instead of feeding into the grid. Due to the time mismatch of the electricity consumption of households and solar-generated electricity, a high share of electricity might be fed into the grid beyond a specific PV system size installed. In this case, the increase in revenue due to the additional PV system capacity installed is low. However, when the costs of the larger PV system size exceed the additional revenue generated, the financial viability of the PPA will decrease from the third-party perspective. The size of the BESS installed depends on the PV system size installed and the daily electricity consumption of the customer.

In the current PPA setting, the BESS charges the excess solar-generated electricity that remains after covering the electricity consumption of the customer and solely discharges to meet the customer's demand at solar-generated electricity shortage times. Consequently, the size of the BESS is ideally large enough to store all the excess solar-generated electricity and to discharge all of its electricity stored to the customer.

We expect that installing a BESS of a specific size increases the electricity bill savings of the customer, as the third-party affords all BESS related costs and the customers benefit from higher self-sufficiency. In contrast, the financial impact of a BESS of a specific size on the financial viability of solar-and-storage PPAs for the third-party is not clear in advance. Similar to the financial trade-off of PV system costs and revenue, the BESS costs oppose the additional revenue resulting from the increased self-consumption. If the increase in self-consumption due to BESS installation is too low, the BESS costs exceed the resultant revenue, mitigating the financial viability of PPAs for third-parties. Consequently, the sizing of the PV system and the BESS is a critical factor in assessing the financial viability of PPAs and must be carefully chosen by taking into account the electricity consumption of the customer and the trade-off between the system costs and the generated revenue.

Some solar PPA contracts also include the option for the customer to buy the PV system from the third-party after the duration or a predetermined number of years (Cory et al., 2008). Most likely, the third-parties only agree to this clause if they are rather interested in the tax incentives or government rebates on the RES than in an investment with long-term cash inflows (Cory et al., 2009). After the PPA expiry, the third-party can also extend the contract or claim to disassemble the system. We assume that this clause can also be included in solar-and-storage PPAs valid for the combined PV+BESS.

2.2 The Econometric Framework

To assess the economic viability of solar and solar-and-storage PPAs, respectively, it is crucial to calculate the Net Present Value (NPV) as a metric for decision-making from the third-parties perspective.

Equation (1) represents the calculation of the NPV as the difference between the sum of the annual discounted cash flows $CF_i \in \mathbb{R}$ for each year $i \in \{1, \dots, T\}$ and the initial investment costs $I_0 \in \mathbb{R}^+$ incurred in the setup year of the PPA

$$\boldsymbol{NPV} = \sum_{\mathbf{i=1}}^{\boldsymbol{T}} \frac{\boldsymbol{CF_i}}{(\mathbf{1} + \mathbf{r}^{\mathbf{TP}})^{\boldsymbol{i}}} - \boldsymbol{I_0}. \tag{1}$$

Therefore, T denotes the duration of the PPA and r^{TP} the discount rate for the third-party, which we assume constant over time. A positive NPV indicates the investment in PPA to be financially viable for the third-party. Furthermore, the higher the NPV, the more economically beneficial is the investment.

The annual cash flow CF_i in year i displayed in equation (2) results from the difference of the cash inflows consisting of the electricity payments of the customer as well as the revenue originating from feeding the surplus electricity into the grid, and the cash outflow consisting of the annual operating and maintenance costs $C_i^{O\&M} \in \mathbb{R}^+$ for the PV system and PV+BESS installed, respectively,

$$\boldsymbol{CF_i} = \sum_{\mathbf{t=1}}^{\boldsymbol{n_i}} (\boldsymbol{p_{i,t}^{PPA}} * \boldsymbol{E_{i,t}^{sc}} + \boldsymbol{p_{i,t}^{feedin}} * \boldsymbol{E_{i,t}^{feedin}}) - \boldsymbol{C_i^{O\&M}}. \tag{2}$$

For each year $i \in \{1, \dots, T\}$, we determine the annual cash inflows based on half-hourly time periods $t \in \{1, \dots, n_i\}$, where n_i is the number of half hours in year i. Thus, $p_{i,t}^{PPA} \in \mathbb{R}^+$ denotes the PPA price per kWh at time t in year i fixed in the PPA and $E_{i,t}^{sc} \in \mathbb{R}^+$ the corresponding amount of electricity self-consumed in kWh billed to the customer by $p_{i,t}^{PPA}$. $p_{i,t}^{feedin} \in \mathbb{R}^+$ denotes the FiT per kWh within at time t in year i and $E_{i,t}^{feedin} \in \mathbb{R}^+$ the corresponding amount of electricity fed into the grid in kWh and billed by $p_{i,t}^{feedin}$. We assume an annual escalation rate ϵ for the initial PPA price $p_0^{PPA} \in \mathbb{R}^+$ which leads to a PPA price of

$$\boldsymbol{p_{i,t}^{PPA} = p_0^{PPA} * (1 + \epsilon)^{i-1}} \tag{3}$$

in year i for $t \in n_i$. The initial investment costs I_0 comprises the investment costs for the PV system $I_0^{PV} \in \mathbb{R}^+$ and the investment costs for the BESS all-in-one unit $I_0^{BESS} \in \mathbb{R}^+$

$$\boldsymbol{I_0 = I_0^{PV} + I_0^{BESS}}. \tag{4}$$

The operation and maintenance (O&M) costs $C_i^{O\&M} \in \mathbb{R}^+$ in year i comprises the O&M costs for the PV system $C_i^{O\&M,\ PV} \in \mathbb{R}^+$ and the O&M costs for the BESS all-in-one unit $C_i^{O\&M,\ BESS} \in \mathbb{R}^+$ in year i

$$\boldsymbol{C_i^{O\&M} = C_i^{O\&M,PV} + C_i^{O\&M,BESS}}. \tag{5}$$

Note that in the case of solar PPA $I_0^{BESS} = 0$ and $C_i^{O\&M,BESS} = 0$ applies as no BESS is installed. From the customer perspective, the amount of electricity bill savings due to entering into a PPA is a decisive reason for concluding the contract. Therefore, equation (6) computes the present value of the electricity bill savings sav of the customer

$$\boldsymbol{sav = \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i} (p_{i,t}^{retail} - p_{i,t}^{PPA}) * E_{i,t}^{sc}}{(1 + r^{cust})^i}}, \tag{6}$$

where the annual discount rate for the customer $r^{cust} \in \mathbb{R}$ is assumed to be constant over time. Thus, the electricity bill savings of the customer at time t in year i result from the spread of the retail tariff $p_{i,t}^{retail}$ and PPA price $p_{i,t}^{PPA}$ weighted by the amount of electricity self-consumed $E_{i,t}^{sc}$ at the same period. We assume the same escalation rate for the retail tariff as for the PPA price, which leads to

$$\boldsymbol{p_{i,t}^{retail} = p_0^{retail} * (1 + \epsilon)^{i-1}} \tag{7}$$

for all t.

Self-consumption and self-sufficiency are well-known ratios in the literature (Luthander et al., 2015) to measure the share of electricity that households draw from PV and PV+BESS generation, respectively. The self-consumption $SC_{i,t}$ at time t in year i defines the share of electricity self-consumed by the customer with respect to the electricity generated $E_{i,t}^{gen} \in \mathbb{R}^+$

$$\boldsymbol{SC_{i,t} = \frac{E_{i,t}^{sc}}{E_{i,t}^{gen}}}. \tag{8}$$

As the capacity of solar panels fades over time, we implement an annual exponential degradation rate $\gamma \in [0,1]$ to the nominal capacity of the PV system installed $C_0^{PV} \in \mathbb{R}^+$ at the time of installation $t = 0$. Hence, we calculate the electricity generated $E_{i,t}^{gen}$ at time t in year i based on the electricity generation profile $E_{i,t}^{gen,norm} \in \mathbb{R}^+$ resulting from the stationary bootstrapping and normalised to a 1 kW PV system installed by

$$\boldsymbol{E_{i,t}^{gen} = E_{i,t}^{gen,norm} * (1-\gamma)^i * C_0^{PV}}, \tag{9}$$

where $i \in \{1, \dots, T\}$ denotes the corresponding year.

The self-sufficiency $SS_{i,t}$ at time t in year i is the share of electricity self-consumed by the customer with respect to his/her electricity consumption $E_{i,t}^{con} \in \mathbb{R}^+$ at time t in year i

$$\boldsymbol{SS_{i,t} = \frac{E_{i,t}^{sc}}{E_{i,t}^{con}}}. \tag{10}$$

Note that $SC_{i,t} \in [0,1]$ and $SS_{i,t} \in [0,1]$ by definition. Both self-consumption and self-sufficiency directly influence the financial viability of PPAs, as explained in the following.

The amount of electricity that is fed into the grid $E_{i,t}^{feedin} \in \mathbb{R}^+$ at time t in year i is the surplus share of electricity generation remaining after the customer's self-consumption and, thus, is given by[2]

$$\boldsymbol{E_{i,t}^{feedin} = \left(1 - SC_{i,t}\right) * E_{i,t}^{gen}}. \tag{11}$$

Inserting (11) and (8) in (1) leads to

$$\boldsymbol{NPV = -I_0 + \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i}\left(p_{i,t}^{PPA} * SC_{i,t} + p_{i,t}^{feedin} * \left(1 - SC_{i,t}\right)\right) * E_{i,t}^{gen} - C_i^{O\&M}}{(1+r^{TP})^i}} \tag{12}$$

$$\boldsymbol{= \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i}\left(p_{i,t}^{PPA} - p_{i,t}^{feedin}\right) * E_{i,t}^{gen} * SC_{i,t}}{(1+r^{TP})^i} + \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i} p_{i,t}^{feedin} * E_{i,t}^{gen} - C_i^{O\&M}}{(1+r^{TP})^i} - I_0}. \tag{13}$$

Furthermore, rewriting (6) by considering (10) results in

$$\boldsymbol{sav = \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i}(p_{i,t}^{retail} - p_{i,t}^{PPA}) * E_{i,t}^{con} * SS_{i,t}}{(1+r^{cust})^i}}, \tag{14}$$

Equation (14) shows that the self-sufficiency serves as a metric to understand which share of the total electricity consumption of the customer is supplied by the electricity generated and, thus, billed at the PPA tariff.

Furthermore, note that by substituting $E_{i,t}^{sc}$ with $SS_{i,t} * E_{i,t}^{con}$, it holds

$$\boldsymbol{SS_{i,t} = \frac{E_{i,t}^{sc}}{E_{i,t}^{con}} = SC_{i,t} * \frac{E_{i,t}^{gen}}{E_{i,t}^{con}}}. \tag{15}$$

which leads to electricity bill savings of

$$\boldsymbol{sav = \sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i}(p_{i,t}^{retail} - p_{i,t}^{PPA}) * E_{i,t}^{gen} * SC_{i,t}}{(1+r^{cust})^i}}. \tag{16}$$

Additionally,the condition

$$\boldsymbol{\left(p_{i,t}^{PPA} - p_{i,t}^{feedin}\right) * E_{i,t}^{gen} > 0}, \tag{17}$$

[2] This formula holds for a solar PV system as sole electricity source, but only approximatively with the additional implementation of a BESS due to the efficiency loss during charging and discharging.

$$(\boldsymbol{p_{i,t}^{retail} - p_{i,t}^{PPA}}) * \boldsymbol{E_{i,t}^{gen}} > \boldsymbol{0}, \tag{18}$$

$$\boldsymbol{r^{TP}, r^{cust}} > \boldsymbol{0} \tag{19}$$

holds for all i, t for $p_{i,t}^{feedin} < p_{i,t}^{ppa}$ and $p_{i,t}^{ppa} < p_{i,t}^{retail}$.

Consequently both terms $\sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i} \left(p_{i,t}^{PPA} - p_{i,t}^{feedin} \right) * E_{i,t}^{gen}}{(1+r^{TP})^i} > 0$ and $\sum_{i=1}^{T} \frac{\sum_{t=1}^{n_i} (p_{i,t}^{retail} - p_{i,t}^{PPA}) * E_{i,t}^{gen}}{(1+r^{cust})^i} > 0$ are positive for $p_{i,t}^{feedin} < p_{i,t}^{ppa}$ and $p_{i,t}^{ppa} < p_{i,t}^{retail}$ and both metrics NPV and savings are increasing in $SC_{i,t}$. Hence, if $p_{i,t}^{ppa} < p_{i,t}^{retail}$ and $p_{i,t}^{feedin} < p_{i,t}^{ppa}$ for all i and t, the best option to increase the financial viability of the PPA for both parties is to increase the customer's self-consumption as much as possible. The additional installation of BESS can achieve this.

In the residential sector, a BESS increases the household's self-consumption by redistributing the electricity generated to higher self-consumption and less electricity fed in. The following technical characteristics of the BESS are applied to model the BESS and its financial impact on PPAs. We derived the technical characteristics from those listed in the battery storage table provided by SolarQuotes (2021). Similar technical characteristics have been taken into account by, e.g. the authors in Hayat et al. (2019), Mulleriyawage and Shen (2020), Oliva H. et al. (2019) and Parra and Patel (2016).

Nominal storage capacity

The nominal storage capacity $C_0^{BESS} \in \mathbb{R}^+$ measured in kWh indicates the total amount of electricity the BESS can store theoretically at the time of installation. Due to technical reasons (see definition of round trip efficiency and state of charge), the nominal capacity is never fully utilized and degrades over time. Section *Modelling storage control strategy* explains the battery degradation model implemented.

Round Trip Efficiency

The round trip efficiency $\eta \in [0,1]$ in percent indicates the proportion of energy lost by a complete cycle[3] of the BESS. Thus, it defines the share of electricity charged to the battery that can be retrieved later. We model both the percentage of electricity loss resulting from either charging or discharging as the square root of the round trip efficiency $\sqrt{\eta}$.

(Dis-)Charging rate

The (dis-)charging rate $\rho \in \mathbb{R}^+$ in kWh is the maximum amount of electricity the BESS can (dis-)charge within one period. Hence, it defines how fast the BESS (dis-)charges the amount of electricity.

State of Charge

State of Charge SoC in percent defines the level of BESS charge relative to the nominal storage capacity at a given time. A total discharge of the BESS by 100% will cause damage to the battery. Therefore, the SoC is limited by an upper bound SoC_{max} and a lower bound SoC_{min} Most warranty documents of BESS include the condition that the declared SoC_{min} and SoC_{max} must not be undercut or exceeded, respectively. Thus, we define the BESS to operate within the given limits following

$$\boldsymbol{SoC_{min} \leq SoC \leq SoC_{max}}. \tag{20}$$

[3] We define a cycle as one charging and discharging operation of the BESS.

For the sake of simplicity, we denote the BESS as full if the SoC reaches its maximum level SoC_{max} and as empty if the SoC reaches its minimum level SoC_{min}.

Control Strategy

We identified the control strategy according to the financial and technical setting in PPAs outlined before. We adopt a load based and not grid-connected control strategy to determine the BESS cycling, as we identified as the best option to increase the financial viability for both the customer and the third-party to increase self-consumption. We call our control strategy the 'evening discharge strategy', consistent with a similar control strategy implemented in Roberts et al. (2019b)[4]. Hence, the available electricity quantities, such as electricity consumption and generation, control the BESS cycling independently of the respective electricity prices like retail, PPA or FiT. Furthermore, the BESS operates exclusively to charge the electricity generated from PV and discharge the stored electricity to the customer. However, the BESS neither charges electricity from the grid nor discharges electricity to the grid. Thus, the BESS solely operates off-grid.

Figure 2 graphically illustrates the evening discharge strategy.

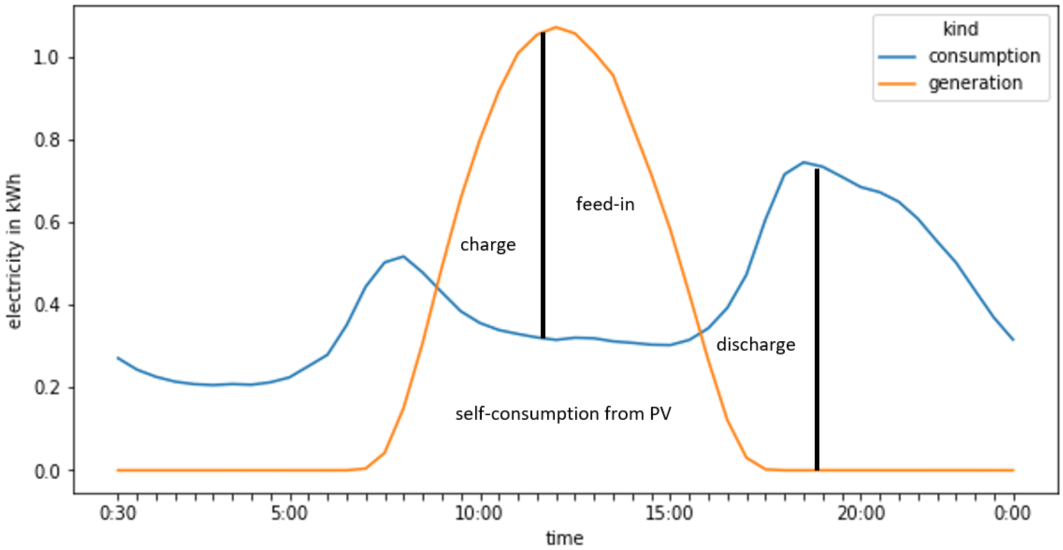

Figure 2: Illustrative distribution of the electricity generated when applying the proposed 'evening discharging strategy'

The control strategy behaves as follows:

If the electricity generation exceeds the electricity consumption, the BESS charges the surplus electricity generated, taking into account the current SoC and the maximum charging rate. Suppose the BESS is not full already and the surplus electricity generated does not exceed the maximum charging rate. In that case, the BESS charges the total surplus electricity generated or till the maximum SoC is reached. If the surplus electricity generated exceeds the maximum charging rate, the BESS charges the maximum charging rate or till the maximum SoC is reached. If the BESS is full already, the BESS does not operate, and the surplus electricity is fed into the grid.

[4] Roberts et al. (2019b) implement multiple control strategies of which one is similar to the control strategy used in this study. However, the authors define fix times for discharging and we couple the discharging process to electricity consumption and generation independently of the time.

In contrast, if the electricity consumption exceeds the electricity generation, the BESS discharges to meet the electricity demand of the customer, while again considering the current SoC and the maximum discharging rate. Suppose the BESS is not empty already and the surplus amount of electricity to consume does not exceed the maximum discharging rate. In that case, the BESS discharges the total surplus amount of electricity to consume or till the minimum SoC is reached. Otherwise, if the surplus electricity consumed exceeds the maximum discharging rate, the BESS discharges the maximum discharging rate or till the minimum SoC is reached. If the BESS is empty already, the BESS does not operate, and the customer draws the surplus electricity from the grid.
Note that the BESS either charges, discharges or stands still, but simultaneous charging and discharging is not possible.

Modelling storage control strategy

To measure the potential amount of electricity that is available to either charge or discharge the BESS, we calculate the control variable $\Delta E_{i,t}^{storage} \in \mathbb{R}$ for each time t in year i as

$$\Delta \boldsymbol{E}_{\boldsymbol{i,t}}^{\boldsymbol{storage}} = \boldsymbol{E}_{\boldsymbol{i,t}}^{\boldsymbol{gen}} - \boldsymbol{E}_{\boldsymbol{i,t}}^{\boldsymbol{con}}, \tag{21}$$

where $E_{i,t}^{gen} \in \mathbb{R}^{+}$ denotes the electricity generated in kWh and $E_{i,t}^{con} \in \mathbb{R}^{+}$ the electricity consumed by the customer in kWh at time t in year i. If $\Delta E_{i,t}^{storage}$ is negative, the electricity consumed exceeds the electricity generated, which indicates the possibility to discharge the BESS by $|\Delta E_{i,t}^{storage}|$ at time t in year i. Otherwise, if $\Delta E_{i,t}^{storage}$ is positive, the electricity generated exceeds the electricity consumed, which indicates the possibility to charge the BESS by $\Delta E_{i,t}^{storage}$ at time t in year i. If the electricity generated equals the electricity consumed in time t the BESS will stand still. Equation (19) displays the implemented control rule

$$\Delta \boldsymbol{E}_{\boldsymbol{i,t}}^{\boldsymbol{storage}} \begin{cases} < \boldsymbol{0}, & \boldsymbol{discharge} \\ > \boldsymbol{0}, & \boldsymbol{charge} \\ = \boldsymbol{0}, & - \end{cases}. \tag{22}$$

Note that $\Delta E_{i,t}^{storage}$ measures either the absolute amount of electricity the consumer can draw from the BESS or the surplus electricity after the consumer's electricity consumption available to charge the BESS.
As described above, the amount of electricity the BESS can charge or discharge is additionally limited by the (dis-)charging rate ρ and the State of Charge $SoC_{i,t-1}$ of the BESS before cycling at time t in year i. If $\Delta E_{i,t}^{storage}$ is negative and, thus, indicates the possibility to discharge the BESS at time t in year i, equation (23) calculates the maximal amount of electricity the BESS can discharge $\Delta SoC_{i,t}^{discharge}$ without violating the SoC condition (20)

$$\Delta \boldsymbol{SoC}_{\boldsymbol{i,t}}^{\boldsymbol{discharge}} = \left(\boldsymbol{SoC}_{\boldsymbol{i,t-1}} - \boldsymbol{SoC}_{\boldsymbol{min}}\right) * \boldsymbol{C}_{\boldsymbol{i,t-1}}^{\boldsymbol{BESS}}, \tag{23}$$

where $C_{i,t-1}^{BESS}$ is the nominal capacity of the BESS in kWh at time $t-1$ in year i before capacity degradation[5]. In total, the actual amount of electricity the BESS discharges $\Delta E_{i,t}^{discharge}$ at time t in year i results in

$$\Delta E_{i,t}^{discharge} = \begin{cases} \min\left(|\Delta E_{i,t}^{storage}|, \sqrt{\eta} * \rho,\ \sqrt{\eta} * \Delta SoC_{i,t}^{discharge}\right), & \Delta E_{i,t}^{storage} < 0 \\ 0, & else \end{cases}, \tag{24}$$

where η is the round trip efficiency. Note that $\Delta E_{i,t}^{discharge}$ is the amount of electricity after efficiency loss due to discharging and the actual amount of electricity the customer consumes from the BESS and pays for at time t in year i.

Otherwise, if $\Delta E_{i,t}^{storage}$ is positive and, thus, indicates the possibility to charge the BESS at time t in year i, the maximal amount of electricity the BESS can charge $\Delta SoC_{i,t}^{\mathrm{charge}}$ under consideration of the SoC condition (20) is

$$\Delta \boldsymbol{SoC}_{i,t}^{\mathbf{charge}} = \left(\boldsymbol{SoC}_{max} - \boldsymbol{SoC}_{i,t-1}\right) * \boldsymbol{C}_{i,t-1}^{BESS}. \tag{25}$$

Thereby, the actual amount of electricity the BESS charges $\Delta E_{i,t}^{charge}$ at time t in year i is

$$\Delta \boldsymbol{E}_{i,t}^{charge} = \begin{cases} \boldsymbol{min}\left(\sqrt{\boldsymbol{\eta}} * \Delta \boldsymbol{E}_{i,t}^{storage}, \sqrt{\boldsymbol{\eta}} * \boldsymbol{\rho},\ \Delta \boldsymbol{SoC}_{i,t}^{charge}\right), & \Delta \boldsymbol{E}_{i,t}^{storage} > \mathbf{0} \\ \mathbf{0}, & \boldsymbol{else} \end{cases}. \tag{26}$$

Similar to discharging, $\Delta E_{i,t}^{charge}$ is the amount of electricity after efficiency loss due to charging, i.e. the actual amount of electricity additionally stored in the BESS at time t in year i.

$E_{i,t}^{BESS}$ denotes the total amount of electricity stored at time t in year i after the BESS either charged or discharged electricity to the customer calculated by

$$\boldsymbol{E}_{i,t}^{BESS} = \boldsymbol{E}_{i,t-1}^{BESS} + \Delta \boldsymbol{E}_{i,t}^{charge} - \Delta \boldsymbol{E}_{i,t}^{discharge}\left(\sqrt{\boldsymbol{\eta}}\right)^{-1}. \tag{27}$$

Note that the BESS either charges or discharges and, thus, either $\Delta E_{i,t}^{discharge} = 0$ or $\Delta E_{i,t}^{charge} = 0$. Also, the factor $\left(\sqrt{\eta}\right)^{-1}$ is needed to calculate the amount of electricity that the BESS discharges to meet the demand of the customer before efficiency loss due to discharging. Subsequently, the State of Charge $SoC_{i,t}$ after the charging process is

$$\boldsymbol{SoC}_{i,t} = \frac{\boldsymbol{E}_{i,t}^{BESS}}{\boldsymbol{C}_{i,t}^{BESS}}, \tag{28}$$

where $C_{i,t}^{BESS}$ denotes the nominal capacity of the BESS after the charging or discharging process at time t in year i determined by

$$\boldsymbol{C}_{i,t}^{BESS} = \boldsymbol{SOH}_{i,t} * \boldsymbol{C}_{0}^{BESS}. \tag{29}$$

As the BESS capacity declines over time, the State of Health $SOH_{i,t}$ of the battery defines the share of nominal capacity at the time of installation C_0^{BESS} that can be utilised at time t in year i under consideration of the technical restrictions. We follow Hesse et al. (2017) to model the nominal storage capacity degradation in each time t of year i. In general, BESS capacity decreases firstly due to

[5] Assume $t = 0$ for a given year i. Then we set $Soc_{i,t-1}^{BESS} := Soc_{i-1,n_{i-1}}^{BESS}$ in equation (23), i.e. we take the value from the last period in the previous year. We assume the same procedure for each recursive calculation.

calendaric degradation and secondly due to cyclic degradation. Calendaric degradation describes the loss of nominal capacity over time because of the BESS self-discharge, i.e. the loss of nominal capacity when the BESS neither charges nor discharges within the entire time. The cyclic degradation describes the loss of capacity due to the number of Equivalent Full Cycles[6] (EFC) the BESS conducts. As suggested in Hesse et al. (2017), we assume a calendaric degradation to 80% SOH after 15 years (:= $T_{80\%}^{cal}$) and a cyclic degradation to 80% SOH after 10000 cycles (:= $T_{80\%}^{cyc}$). Therefore, equation (30) describes the state of health SOH_t after charging or discharging at time t

$$\boldsymbol{SOH_{i,t} = 1 - \left(age_{i,t}^{cal} + age_{i,t}^{cyc}\right) * 0.2}, \tag{30}$$

where $age_{i,t}^{cal}$ denotes the calendaric degradation and $age_{i,t}^{cyc}$ the cyclic degradation of the BESS at time t in year i. Note that if $age_{i,t}^{cal} + age_{i,t}^{cyc} = 1$ the state of charge amounts to $SOH_{i,t} = 80\%$. The calendaric degradation $age_{i,t}^{cyc}$ at time t in year i results from the proportion of the time interval $\Delta t = t - (t-1)$ in the calendric time indicator $T_{80\%}^{cal}$

$$\boldsymbol{age_{i,t}^{cal} = age_{i,t-1}^{cal} + \frac{\Delta t}{T_{80\%}^{cal}}}, \tag{31}$$

and the cyclic degradation at time t in year i amounts to

$$\boldsymbol{age_{i,t}^{cyc} = age_{i,t-1}^{cyc} + 0.5 * \frac{\left(\Delta E_{i,t}^{charge} + \left|\Delta E_{i,t}^{discharge}\right| \left(\sqrt{\eta}\right)^{-1}\right)}{C_{i,t-1}^{BESS} * T_{80\%}^{cyc}}}. \tag{32}$$

The calendric time indicator $T_{80\%}^{cal}$ denotes the period within which the state of health decreases to 80% solely due to calendaric degradation and, similarly, the cyclic time indicator $T_{80\%}^{cyc}$ denotes the number of EFCs the BESS can perform to reach 80% state of health solely due to cyclic degradation. This means that it holds

$$\boldsymbol{age_{T_{80\%}^{cal}}^{cal} = 1} \text{ and } \boldsymbol{age_{T_{80\%}^{cyc}}^{cyc} = 1}, \tag{33}$$

as well as

$$\boldsymbol{SOH_{T_{80\%}^{cal}} = 80}\% \text{ assuming } \boldsymbol{age_{T_{80\%}^{cyc}}^{cyc} = 0} \tag{34}$$

and

$$\boldsymbol{SOH_{T_{80\%}^{cyc}} = 80}\% \text{ assuming } \boldsymbol{age_{T_{80\%}^{cyc}}^{cal} = 0}. \tag{35}$$

At initialisation, we set

$$\boldsymbol{age_{0,0}^{cal} \coloneqq 0} \text{ and } \boldsymbol{age_{0,0}^{cyc} \coloneqq 0}. \tag{36}$$

As already mentioned, under solar-and-storage PPAs, the BESS installed operates solely to meet the demand of the customer and, thus, affects the share of self-consumption. However, the electricity generated $E_{i,t}^{gen}$ at time t in year i is either self-consumed by the customer or fed into the grid. The amount of electricity self-consumed $E_{i,t}^{sc}$ at time t in year i derives from

[6] 'Equivalent Full Cycle is defined by the overall energy throughput (counting either only charge or only discharge direction) with any DOD per cycle divided by the available capacity' (Hesse et al. (2017))

$$\boldsymbol{E_{i,t}^{sc}} = \mathbf{min}(\, \boldsymbol{E_{i,t}^{gen}} + \, \Delta\boldsymbol{E_{i,t}^{discharge}},\, \boldsymbol{E_{i,t}^{con}}\,), \tag{37}$$

where $\Delta E_{i,t}^{discharge} \in \mathbb{R}^{+}$ denotes the amount of electricity discharged to the customer at time t in year i resulting from the evening discharging strategy implemented. Note that in the case of solar PPA it holds $\Delta E_{i,t}^{discharge} = 0$ for each time t of year i. With $\left(\sqrt{\eta}\right)^{-1} * \Delta E_{i,t}^{charge}$ as the amount of electricity charged to the BESS at time t in year i with round trip efficiency η

$$\boldsymbol{E_{i,t}^{feedin}} = \begin{cases} \boldsymbol{E_{i,t}^{gen}} - \, \boldsymbol{E_{i,t}^{sc}} - \left(\sqrt{\boldsymbol{\eta}}\right)^{-1} * \Delta\boldsymbol{E_{i,t}^{charge}}, & \boldsymbol{E_{i,t}^{sc}} + \left(\sqrt{\boldsymbol{\eta}}\right)^{-1} * \Delta\boldsymbol{E_{i,t}^{charge}} \leq \, \boldsymbol{E_{i,t}^{gen}} \\ \mathbf{0}, & \boldsymbol{E_{i,t}^{sc}} + \left(\sqrt{\boldsymbol{\eta}}\right)^{-1} * \Delta\boldsymbol{E_{i,t}^{charge}} > \boldsymbol{E_{i,t}^{gen}} \end{cases} \tag{38}$$

determines the amount of electricity fed into the grid $E_{i,t}^{feedin}$ at time t in year i. Equation (38) illustrates that $E_{i,t}^{feedin}$ is the surplus of the electricity generated at time t in year i after meeting the demand of the customer $E_{i,t}^{sc}$ and charging the BESS by $\left(\sqrt{\eta}\right)^{-1} * \Delta E_{i.t}^{charge}$ at time t in year i.

3. The Data and Preliminary Analysis

We simulate representative electricity consumption and generation profiles for the financial and technical evaluation of residential solar and solar-and-storage PPAs based on real-world electricity consumption and generation data. This section provides a brief overview of electricity consumption and generation data and discusses how to obtain and simulate representative electricity consumption and generation profiles for our empirical analysis.

1.1 Data description

For the financial analysis of PPAs in Australia, we use data on solar home electricity provided by Ausgrid to obtain representative electricity consumption profiles of Australian households in NSW and the respective electricity generation profiles of PV installed onsite. The data is available at Ausgrid (2021).

The Ausgrid data set contains three years of half-hour gross metered measurements from 01-07-2010 to 30-06-2013 of electricity consumption and generation data for 300 randomly chosen residential customers from Ausgrid who have a PV installed within the period. For each customer, the data set also provides a unique ID, the postcode where the customer lives, and the capacity of the PV system. To make the amount of solar-generated electricity per customer comparable and scalable, we normalise the half-hour electricity generation data of each customer with the PV capacity installed to a 1 kW PV system installed.

There are customers with unusually high or low annual electricity consumption and PV systems that generate an exceptionally high or low amount of electricity per year in the data set. To eliminate the influence of these outliers on the simulation of representative electricity profiles, we clean the data set by households with top or bottom 2.5% annual electricity consumption and generation, respectively. After cleaning, 239 customers remain for further analysis, which we call the cleaned data set. The remainder of this section provides an overview of the electricity consumption and generation data included in the cleaned data set.

Distribution of annual electricity consumption

Figure 3 graphically illustrates the distribution of the annual electricity consumption in kWh within the periods 07/2010 - 06/2011, 07/2011 - 06/2012 and 07/2012 - 06/2013 of the 239 customers in the cleaned data set.

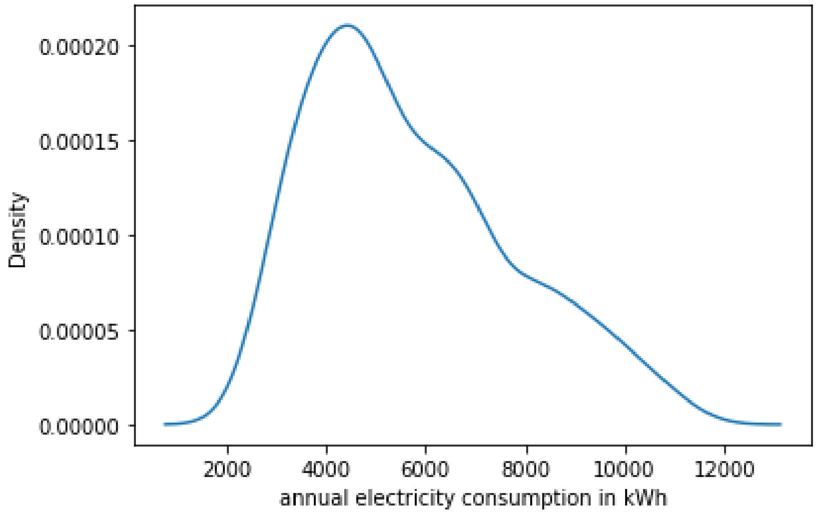

Figure 3. Kernel density plot of annual electricity consumption across 239 households

On average, the customers consume 5722.07 kWh per year, with the lowest annual electricity demand per customer at 2430.75 kWh and the highest at 11458.18 kWh. The distribution is slightly right skewed and shows a high variation around the mean. With 5252.96 kWh, the median annual electricity consumption is by 469.10 kWh lower than the mean, which means that half of the customers have a lower electricity consumption than on average. The standard deviation amounts to 2048.44 kWh, whereby the 25% quantile lies at 4133.98 kWh and the 75% quantile at 6999.46 kWh.

Average electricity profile of daily electricity consumption

Figure 4 shows the time series of mean daily electricity consumption in kWh of the cleaned data set within the period from 01-07-2010 to 30-06-2013.

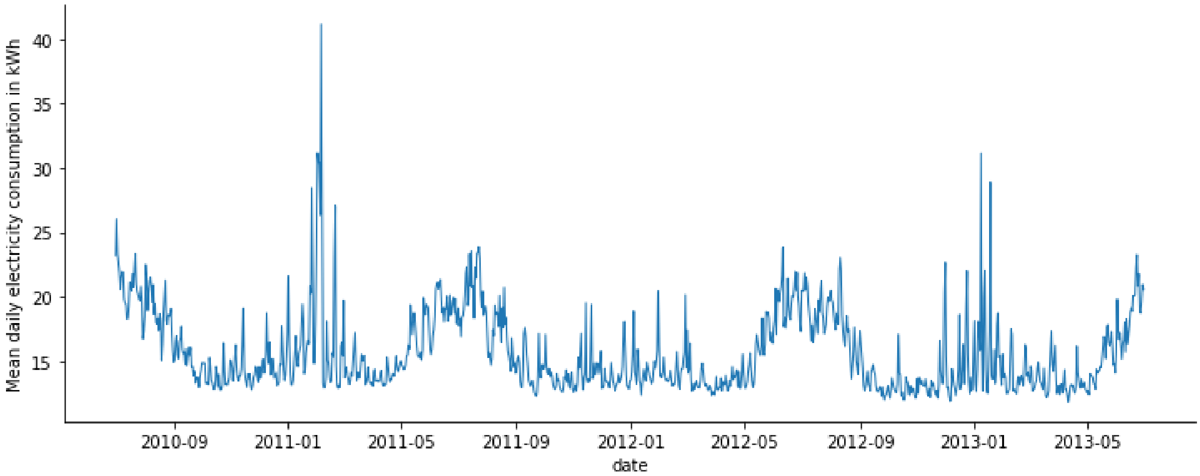

Figure 4: Average daily electricity consumption from 01-07-2010 to 30-06-2013

The time series of mean electricity consumption displays a seasonal dependency, as the daily electricity consumption decreases from winter to spring and again increases from autumn to winter. This behaviour is typical for residential electricity consumption, as households use more electricity in winter to heat their homes. In summer, especially in February 2011 and January 2013, some days occur with unusually high daily electricity consumption. Many residents in Australia have cooling units installed, resulting in higher residential electricity demand on hot days. In 2012, 94% of Australian households owned electric air conditioning systems to cool their homes and households used approximately 40% of the total electricity consumption for space conditioning in 2013 (Ryan and Pavia, 2016). In February 2011, a heatwave in New South Wales led to seven days of extraordinary high temperature from January 30th to February 6th with peak temperature at 41.5°C on the 5th of February responsible for the high peak average electricity consumption of 41.17 kWh at this day (Bureau of Meteorology New South Wales Climate Services Centre, 2011). Also, during the summer of 2012/13, Australia faced record temperature, whereas the south of Sydney was affected most in the first week of 2013 till January 8th with temperatures over 40°C (Bureau of Meteorology, 2013). On average, the daily electricity demand per customer is at 18.99 kWh the highest in the winter month (June to August), and at 13.96 kWh the lowest in spring (September to November), followed by autumn (March to May) at 14.40 kWh. The average daily electricity consumption in summer (December to February) amounts on average to 15.30 kWh, which is due to the high outliers on hot summer days.

Distribution of annual electricity generation per kW PV system size installed

Figure 5 displays the distribution of normalised annual electricity generation per kW PV installed onsite the 239 customers in the cleaned data set.

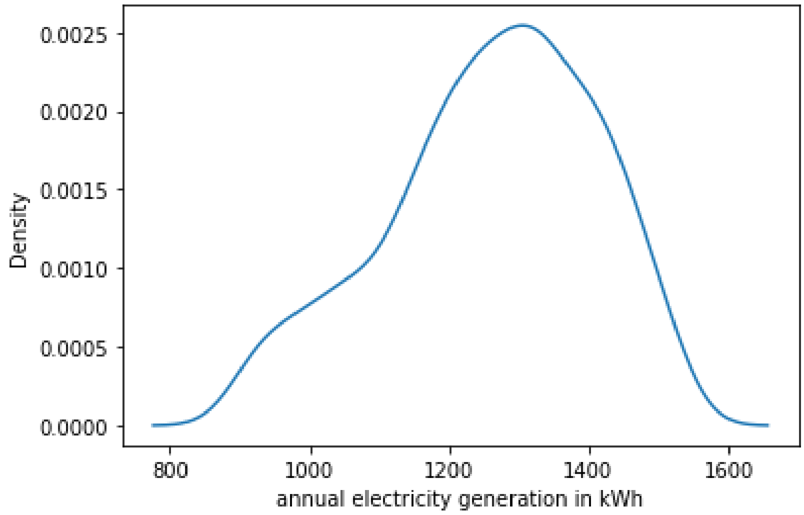

Figure 5: Kernel density plot of annual electricity generation across 239 households

Source: own presentation

The average annual electricity generation amounts to 1260.53 kWh per kW PV installed, with the lowest annual generation at 896.69 kWh and the highest annual generation at 1535.87 kWh. Unlike the distribution of annual electricity consumption, the curve of annual electricity generation is left skewed. The median electricity generation is at 1277.31 kWh per kW PV system installed by only 16.78 kWh higher than the average. The standard deviation amounts to 149.41, which indicates low variation in the data.

Average electricity profile of daily electricity generation

Figure 6 shows the time series of average daily electricity generation in kWh per kW PV system size installed of the customers in the cleaned data set from 01-07-2010 to 30-06-2013.

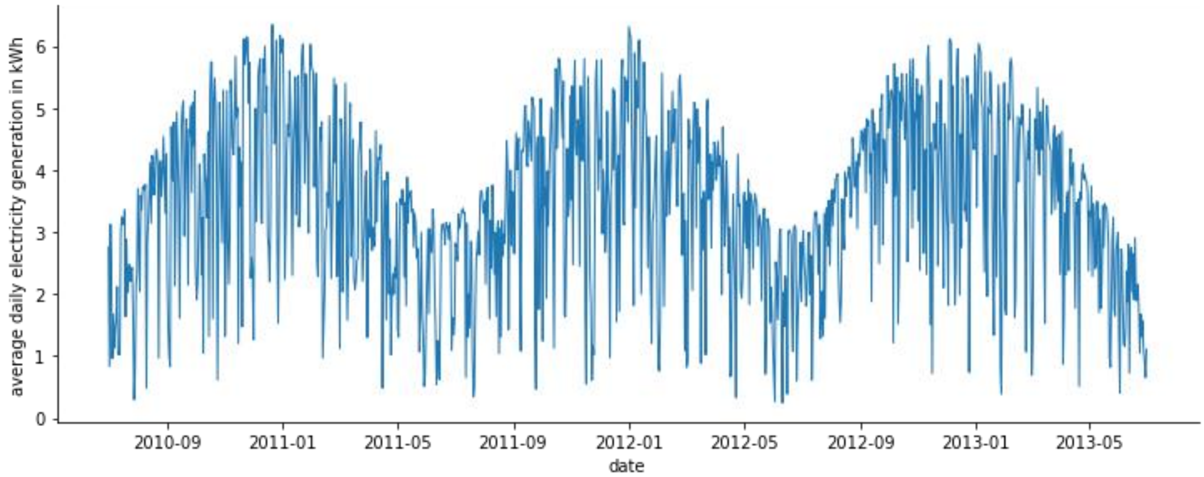

Figure 6: Average daily electricity generation for a 1 kW PV system installed from 01-07-2010 to 30-06-2013

The average daily electricity generation exhibits strong seasonal dependency, as it cycles from low daily electricity generation in winter with a minimum of 0.24 kWh to high peaks in summer with a maximum of 6.35 kWh and back. As expected, high solar radiation on summer days leads to a significant increase in electricity generation, while lower solar irradiation in winter reduces the amount of electricity generated. On average, 1 kW PV system installed generates 2.34 kWh per day in winter, 3.99 kWh per day in spring, 3.16 kWh in autumn and 4.11 kWh in summer.

4. Empirical Results

This section presents the results for the financial and technical assessment of an investment in residential solar and solar-and-storage PPAs, respectively. In particular, we determine the self-consumption and self-sufficiency for PPA customers, the net present value and electricity bill savings for each pair of electricity consumption and generation profile individually. Based on the applied bootstrapping methodology, all results depicted in this section are average values of the calculations conducted.

4.1 Parameters

This section summarises the input parameters applied to evaluate residential solar and solar-and-storage PPAs in a base case scenario.

PV system costs: We scale the investment costs of the PV system along the PV price index of $900 per kW installed, following data provided by Solar Choice (2021a) in March 2021. The PV price index includes the solar inverter costs, the GST and STC discount and represents a price cross-section of residential PV systems purchased in Australia. The PV system has a lifetime of at least 25 years, as suggested in European Photovoltaic Industry Association (2011). We implement a 0.5% annual degradation rate, i.e. a rate that represents the medium degradation rate per year for PV systems (Jordan and Kurtz, 2013). The solar inverter is assumed to be replaced after ten years, which is consistent with Hoppmann et al. (2014), Roberts et al. (2019b) and Best et al. (2019), at 20% of the PV system costs. We assume annual O&M costs for the PV system amounting to 1.5% of the PV system investment costs following Hoppmann et al. (2014).

BESS costs: In solar-and-storage PPAs, the upfront investment costs for BESSs with a hybrid inverter amount to $1430, $1170 and $1000 per kWh installed for nominal storage capacities between 3 kWh - 7 kWh, 8 kWh - 12 kWh and 13 kWh – 17 kWh, respectively, and are derived based on the prices of the all-in-one BESSs[7] provided by SolarQuotes (2021). We set the PV system costs to $720 per kW, as the solar inverter is redundant. The hybrid inverter replacement also takes place after ten years of installation, with costs at 20% of the total upfront investment costs of the PV+BESS. There is little literature regarding the annual O&M costs of a BESS. We follow Carnegie et al. (2013) and assume $25 per kWh installed and year, which are the reported O&M for lithium-ion batteries.

Technical characteristics of the BESS: For the degradation of the BESS, we assume a so-called calendaric degradation to 80% SOH after 15 years and a cyclic degradation to 80% SOH after 10000 cycles, representing a lithium-ion battery according to Hesse et al. (2017). Further parameters, such as round trip efficiency and maximum SoC, are displayed in Table 2 and take typical values for lithium-ion batteries derived from the BESSs provided by SolarQuotes (2021).

PV system and BESS size: Li (2018) and Davidson et al. (2015) analyse a sample of solar lease and PPA contracts in the USA, respectively. Both identify the most common installation size of PV systems under a PPA to be 5 kW. Hence, we implement a PV system with a nominal capacity of $C_0^{PV} = 5$ kW at time of installation in the base case scenario for solar and solar-and-storage PPAs, respectively. For consistency, we assume a BESS with a nominal storage capacity of $C_0^{BESS} = 5$ kWh at time of installation under solar-and-storage PPAs. For the sake of simplicity, BESS size refers to the nominal storage capacity and PV system size to the nominal PV system capacity at time of installation in the following.

Electricity tariffs: In NSW, current FiTs to feed solar-generated electricity into the grid range from 6ct to 16ct per kWh, depending on the retailer (Solar Choice, 2021b). In the base case scenario, the FiT tariff amounts to $0.0665 per kWh, which is the average FiT benchmark in 2020/21 for NSW provided by the Independent Pricing and Regulatory Tribunal (IPART) of NSW (IPART, 2020). Furthermore, we analyse the impact of FiT on the financial viability by additionally applying a FiT of $0.0945 per kWh, which is the average benchmark for 2019/20 (IPART, 2019). Note that we assume the FiT as constant over time. We implement the two most common retail tariffs offered in Australia, the flat-rate tariff and TOU tariff, and determine the electricity bill savings for each tariff segment individually (Australian Energy Regulator, 2020). In the following, we denote the customers

[7] All-in-one BESSs consist of a battery unit and a hybrid inverter. Hybrid inverters are able to manage the entire flow of solar-generated electricity, including charging the BESS and feeding the surplus electricity into the grid (Martin II (2015)).

with flat-rate tariffs as ‘flat-rate customers’ and the customers with TOU tariffs as ‘TOU customers’. A flat-rate tariff bills the electricity per kWh with a constant price independently of the amount and daytime of electricity consumed. Under a TOU tariff, the customers pay different prices per kWh for electricity usage within different daytimes. Here, the day is generally divided into peak, shoulder and off-peak times, with the highest prices during peak times and the lowest during off-peak times. TOU tariffs are regulatory instruments for the electricity market to encourage customers to purchase more electricity at off-peak times and less at peak times. We use the tariffs for customers from the electricity distributor Ausgrid with a flat-rate tariff amounting to $0.2952 per kWh and a TOU tariff as displayed in Table 1 (Diamond Energy, 2019).

	Period	**Price**
Peak	2pm-8pm on business days	$0.5445/kWh
Shoulder	7am-2pm & 8pm-10pm on business days, 7am-10pm on weekends/public holidays	$0.2583/kWh
Off-peak	all other times	$0.1975/kWh[8]

Table 1: Time-of-Use (TOU) tariff

As already mentioned, the PPA tariff is often set at a fixed discount on the retail tariff of the customer in solar PPAs. To the best knowledge of the authors, there is no information about the initial PPA tariff valid for residential solar-and-storage PPAs. Thus, we implement an initial PPA tariff of $0.24/kWh in the base case scenario for both solar and solar-and-storage PPA, which equals a discount of approximately 20% of the flat-rate tariff assumed. Additionally, we analyse the sensitivity of the PPA tariff on the financial viability of solar and solar-and-storage PPAs by varying the initial PPA tariff from $0.20/kWh to $0.28/kWh. The price escalation rate amounts to 2.5%, as suggested by SolarChoice (Jeff Sykes, 2020), which we also assume for the retail tariff.

Discount rates:

Consistent with Roberts et al. (2019b) and Sharma et al. (2019), the discount rate for the NPV calculation is set at 6%, displaying a typical discount rate for PV and BESS investments in the residential sector. We assume a 2% discount rate for the customer, as the investment in PPAs is a low-risk investment for the customer. Table 2 summarizes the input parameter applied in the base case scenario.

Parameters	**Symbol**	**Value**
Contract duration	T	20 years
Annual O&M costs for the PV system	$C^{O\&M,PV}$	$13.5
Annual O&M costs for BESS	$C^{O\&M,BESS}$	$25

[8] Note that increasing self-consumption seems to be the best approach to increase the electricity bill savings of the customer under a PPA, if the PPA tariff is below the retail tariff. However, the retail tariff at off-peak times for TOU customers is below the PPA tariff and customers will make financial losses when consuming the electricity generated at off-peak times. This is no problem in solar PPAs, as there is nearly no electricity generation at off-peak times. Under solar-and-storage PPAs, the BESS may supply some of its electricity stored to the customers during off-peak times. We do not change the discharging strategy of the BESS system in this special case, as our results will show that TOU customers extremely profit from the high tariff spread at peak times, balancing the financial losses at off-peak times. Also, the financial viability for the third party is more critical.

PV system		
PV system size	C_0^{PV}	5 kW
Annual degradation rate for PV system	γ	0.5%
PV system costs per kW installed[9]	I_0^{PV}	$900
BESS		
BESS size	C_0^{BESS}	5 kWh
(Dis-)Charging rate	ρ	5 kWh
Round Trip Efficiency	η	92%
Maximum SoC	SoC_{max}	1
Minimum SoC	SoC_{min}	0.1
Control strategy		Evening discharge
Tariffs		
FiT[10]	p^{feedin}	$0.0665/kWh
Initial PPA tariff	p_0^{PPA}	$0.24/kWh
Discount Rates		
Discount rate for TPO	r^{TP}	6.0%
Discount rate for customers	r^{cust}	2.0%

Table 2: Parameter overview for the base case scenario

4.2 Analysis of Storage

This section provides an overview of the performance of the BESS in year one, the start year of the PPA. We analyse the amount of electricity stored in one year and the SoC curve over one week in spring, enabling us to measure the impact of BESS installations on self-sufficiency and self-consumption in a second step as displayed in Section 4.2.1.

Figure 7 depicts the average amount of electricity stored in year one with a 5 kWh BESS installed depending on the PV system size. Note that the amount of electricity stored equals the amount of electricity charged after efficiency loss.

[9] solar PV system price index including GST, small-scale certificate and inverter
[10] Benchmark for FiT in 2020/21 provided by IPART

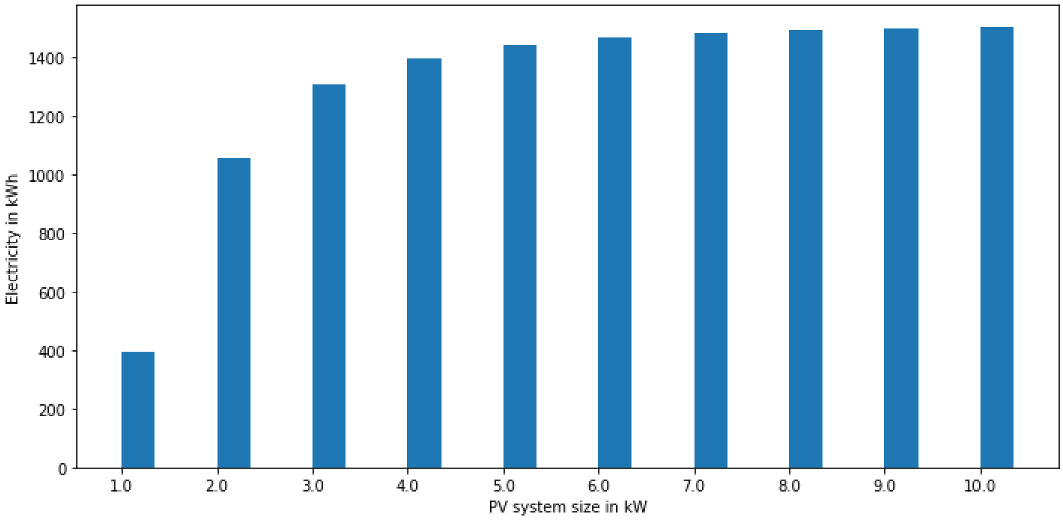

Figure 7: Average amount of electricity stored in year one for different PV system sizes with a 5 kWh BESS installed

For a 1 kW PV system installed, the electricity stored in year one amounts to 394.61 kWh and rises stepwise to 1396.05 kWh for 4 kW installed. When the PV system size surpasses 4 kW, the increase in electricity stored happens in smaller and smaller steps until it reaches 1503.94 kWh for a 10 kW PV system installed. In the base case scenario with a 5 kW PV system size installed, the BESS stores 1440.30 kWh, which is about 22.58% of the electricity generated in year one.

Note that the capacity of the BESS degrades over time resulting in less storage capacity over the years. Consequently, the amount of electricity stored decreases per year as depicted in *Appendix C*. We also refer to *Appendix C* for more information about the degradation parameters such as the SOH of the BESS after 20 years, the remaining capacity of the BESS after 20 years and the cyclic degradation after 20 years.

A closer look at the State of Charge (SoC) explains the decreasing increase of electricity stored with increasing PV system size.

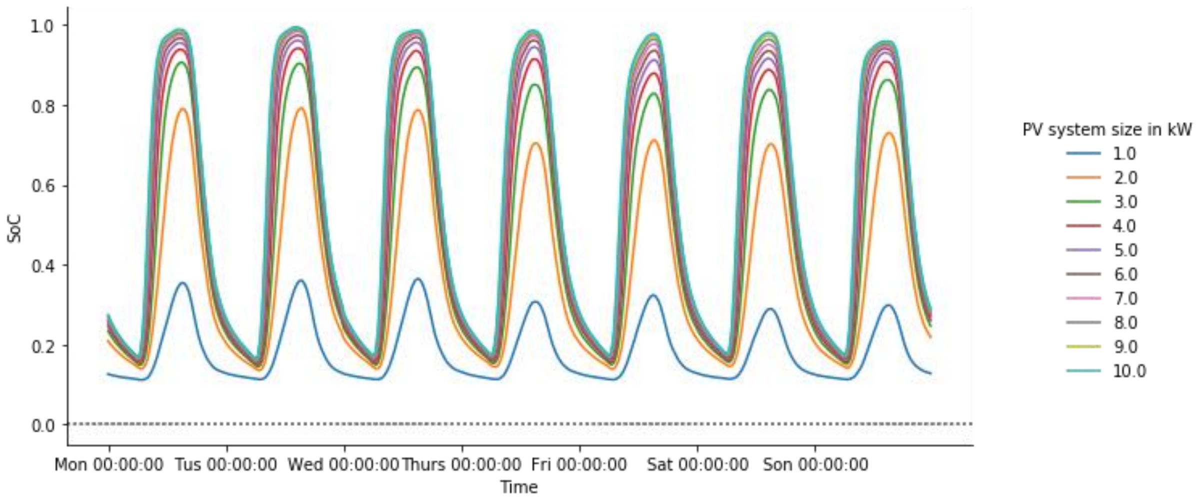

Figure 8: Average State of Charge for one week in spring for different PV system sizes with a 5 kWh BESS installed in year one

Source: own presentation

Figure 8 shows the average half-hourly progress in SoC for one week in spring[11] of year one for different PV system sizes with 5 kWh BESS installed. As described in Section ***Error! Reference source not found.***, the SoC declines when the battery storage discharges electricity to the customer and rises when the battery storage charges electricity from the surplus solar generation left after meeting the demand of the customer. Figure 8 visualises that the battery cycles on average one time per day. For each PV system size, the SoC reaches its maximum value per day in the late afternoon at about 3 pm and decreases to its minimum value per day in the morning at about 7 am. Furthermore, a larger PV system size results in a higher maximum SoC and a higher minimum SoC per day. For a 1 kW PV system installed, the battery storage is only utilised to a maximum of 36.51% per day and is nearly discharged to the minimum bottom limit of $SoC_{min} = 10\%$. With increasing PV system size installed, the maximum SoC per day increases stepwise to 94.10% at 4 kW and rises to 99.40% with 10 kW installed. Thus, for a 5 kWh BESS, the battery storage capacity is nearly fully utilised per day with 4 kW PV installed. For larger PV system size installed, the BESS charges only a small additional share of the electricity generated, and the excess electricity is fed into the grid. Furthermore, the BESS cannot fully discharge its electricity charged per day when the PV system size exceeds 1 kW. The minimum SoC amounts to 14.96% for a 4 kW and 16.45% for a 10 kW PV system size, respectively. In the base case scenario with a 5 kW PV system installed, the SoC cycles from 95.47% at 3 pm and 15.94% at 7 am. Thus, the nominal battery storage capacity of 5 kWh is nearly fully utilised per day.

4.2.1 Self-Sufficiency and Self-Consumption

This section analyses the change in self-sufficiency and self-consumption due to the additional installation of a BESS in year one, the start date of the PPA. Figure 9 shows the total average amount of electricity fed into the grid, and Figure 10 the average amount of electricity self-consumed per PV system size in year one. The blue bars refer to the case of a PV system installed stand-alone, called PV. The orange bars refer to the case of a PV system combined with a BESS of size 5 kWh installed, called PV+BESS. The dashed line in the first panel represents the average annual electricity generation of the respective PV system. The dashed line in the second panel represents the average annual electricity consumption of a household in year one.

Note that for each PV system size installed, the sum of the amount of electricity fed in and the amount of electricity self-consumed for a PV system installed stand-alone nearly equals the one for PV+BESS installed, respectively. The BESS installation redistributes the total amount of electricity generated by reducing the amount of electricity fed into the grid and raising the amount of electricity self-consumed. In doing so, a low amount of electricity is lost due to the round trip efficiency of the BESS.

[11] The SoC shows similar behaviour for all seasons. A slight decrease in the maximum average SoC for low solar PV system sizes is observed in the winter times, as a lower amount of electricity generated is available to store.

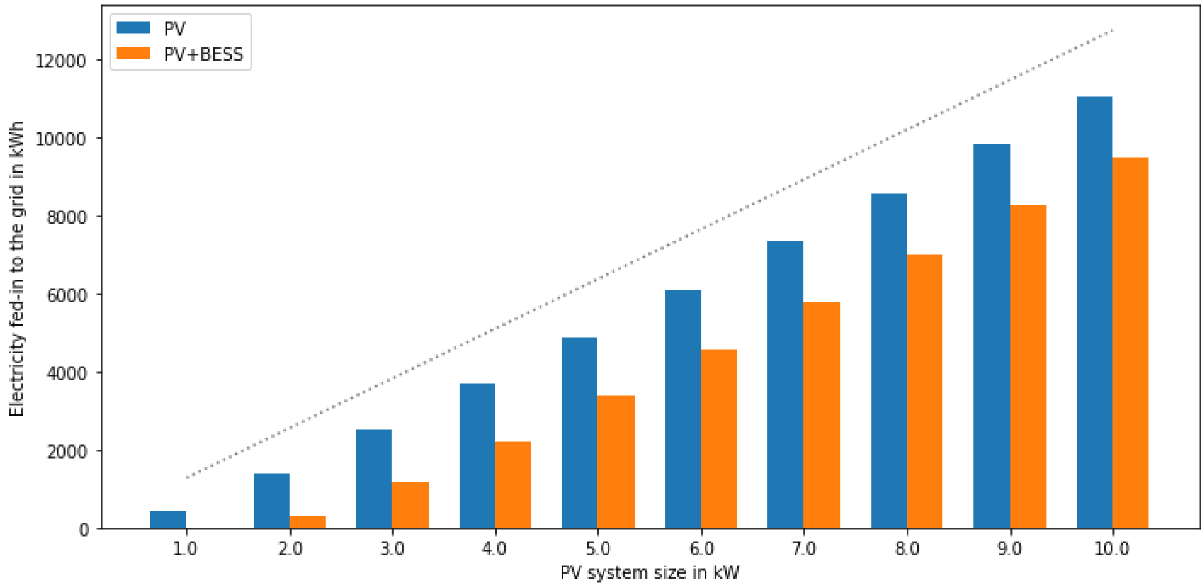

Figure 9: Amount of electricity fed into the grid for different PV system sizes for PV and PV+BESS with a 5 kWh BESS installed in year one

Source: own presentation

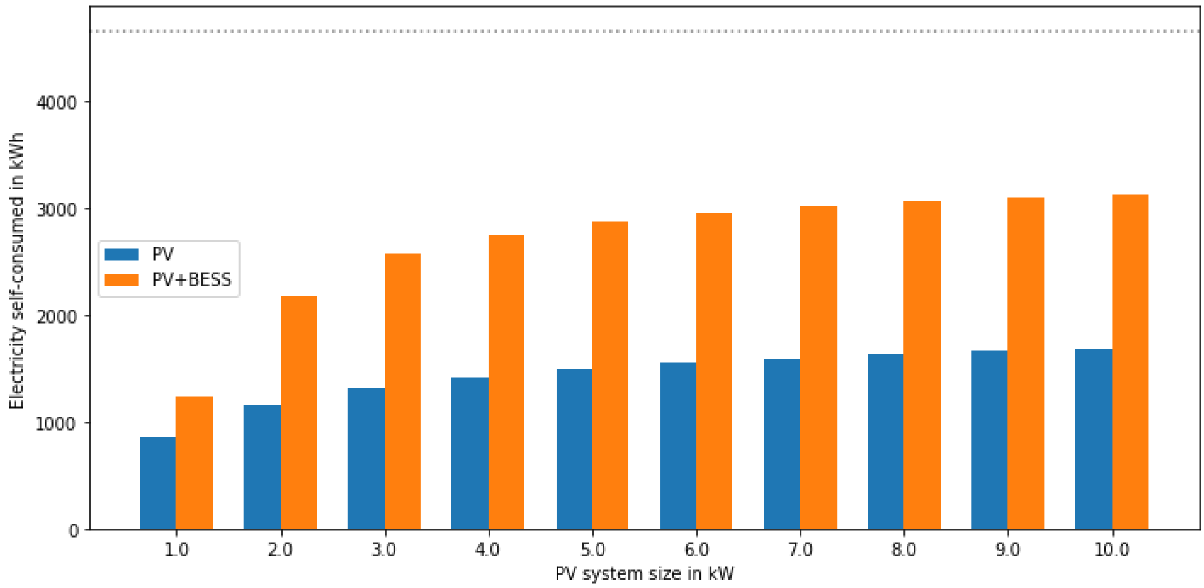

Figure 10: Amount of electricity self-consumed for different PV system sizes for PV and PV+BESS with a 5 kWh BESS installed in year one

Source: own presentation

For both PV and PV+BESS installed, the amount of electricity fed into the grid rises with increasing PV system size, as more electricity generated is available. The amount of electricity fed into the grid starts with 417.81 kWh for a 1 kW PV system installed and reaches 11067.45 kWh for a 10 kW PV system installed, which means that about 32.75% and 86.76% of the electricity generated is fed into the grid, respectively. For the combined installation of a PV system and a 5 kWh BESS, the amount of electricity fed into the grid starts with 6.40 kWh for a 1 kW PV system installed and reaches 9499.49 kWh for a 10 kW PV system installed, which means that about 0.005% and 74.47% of the electricity generated is fed into the grid, respectively. As expected, the amount of electricity fed into the grid is lower with a BESS than without a BESS installed. For example, under the base case scenario with a 5 kW PV system installed, the amount of electricity fed into the grid in year one is 4885.09 kWh and decreases by 30.74% to 3383.47 kWh when adding a 5 kWh BESS. This implies that with 5 kWh BESS installed, 1501.62 kWh less of the electricity generated will be fed into the grid and billed by FiT compared to no BESS installation.

Contrary, the amount of electricity self-consumed is higher with a BESS than without a BESS installed. In the base case scenario with a 5 kW PV system installed, the amount of self-consumption in year one amounts to 1493.11 kWh for a PV system stand-alone and to 2873.45 kW with a 5 kWh BESS installed. Hence, the additional installation of a 5 kWh BESS nearly doubles the amount of electricity self-consumed.

Furthermore, the amount of electricity self-consumed for a PV+BESS installed rises similar to the electricity stored from 1236.18 kWh for a 1 kW PV system stepwise to 2757.60 kWh for a 4 kW PV system installed. From a PV system size of 5 kW, the increase in electricity self-consumed flattens until it reaches 3130.15 kWh at a PV system of size 10 kW. Recalling the calculation of the electricity self-consumed as the sum of the electricity generated and the electricity discharged from the BESS explains the similar behaviour of electricity self-consumed and electricity stored with increasing PV system size. However, with PV stand-alone, the electricity self-consumed starts at 857.83 kW with a 1 kW PV system installed and rises slightly to 1688.945 kWh with a 10 kW PV system installed.

Figure 11 displays the self-sufficiency, and Figure 12 the self-consumption for PV and PV+BESS with our base assumptions.

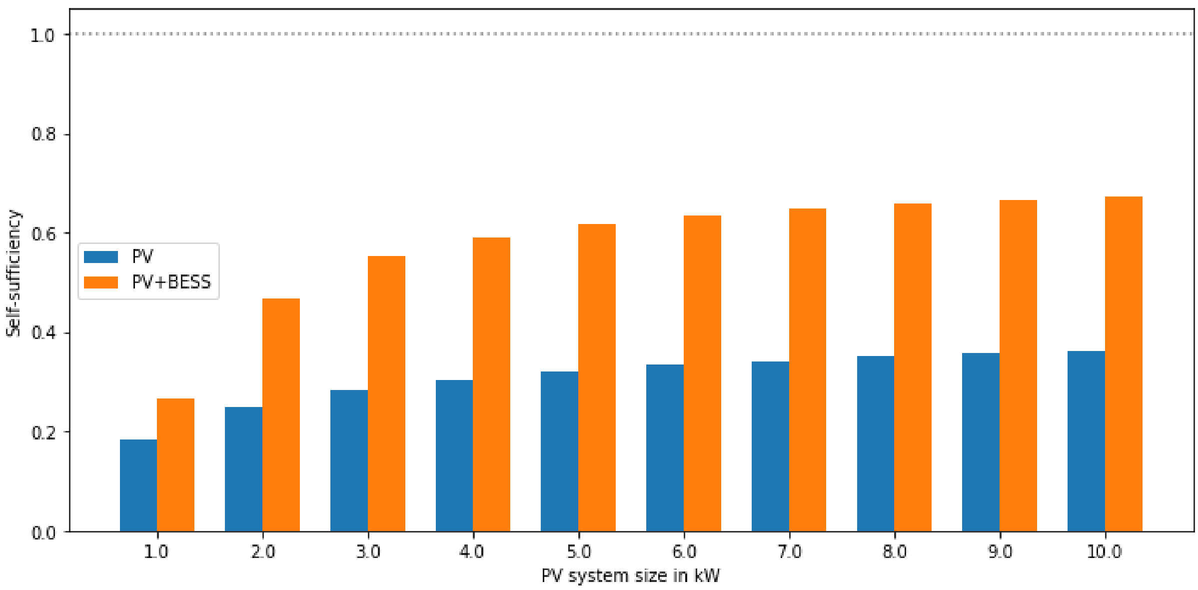

Figure 11: Self-sufficiency for different PV system size for PV and PV+BESS with a 5 kWh BESS installed in year one

Source: own presentation

For both PV and PV+BESS, the self-sufficiency increases with increasing PV system size. The self-sufficiency with only PV installed starts at 18.41% with a 1 kW PV system and increases in small steps to 36.25% with a 10 kW PV system. This means that a household with a 1 (10) kW PV system installed covers 18.41% (36.25%) of its own consumption by solar-generated electricity. One reason for the low self-sufficiency and its slow increase with increasing PV system size is the time mismatch of solar-generated electricity and the electricity consumption of the customer. However, a larger PV system size only contributes a little additional amount of electricity generated at times when the customer demands electricity. The main part of the electricity generated of larger PV system is fed into the grid (cf. Figure 12). Figure 11 illustrates that the self-sufficiency with a PV+BESS installed exceeds the one without a BESS installed. The share of customer's demand met by the electricity generated amounts to 26.53% with a 1 kW PV system installed and increases rapidly to 59.19% with a 4 kW PV system installed. For larger PV system sizes, the self-sufficiency increases in minor steps to 67.19% with a 10 kW PV system installed. As mentioned before, for a 5 kWh BESS installed, the BESS capacity is nearly fully utilised per day with a 4 kW PV system installed. As a result, smaller and smaller amounts of electricity are additionally stored as the PV system size increases, explaining the flattening of the self-sufficiency curve beyond a 4 kW PV system. However, these results indicate that the BESS can partly compensate for the time mismatch of solar-generated electricity and the electricity consumption of the customer. In the base case scenario with a 5 kW PV system installed, the self-sufficiency amounts to 32.05% with PV only and 61.68% with PV+BESS. This means that a surplus of 29.63% of the electricity consumption of the customer can be met by solar-generated electricity when adding a 5 kWh BESS to the PV system. This directly reduces the electricity bill savings of the customer.

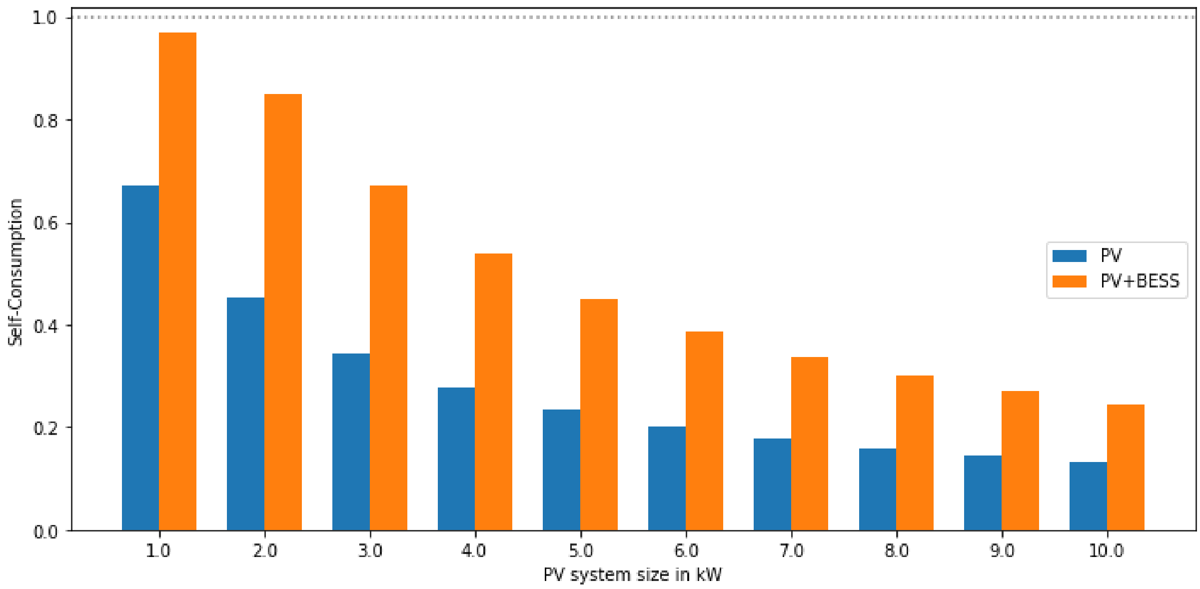

Figure 12: Self-consumption for different PV system size for PV and PV+BESS with a 5 kWh BESS installed in year one

Source: own presentation

Contrary to self-sufficiency, the self-consumption decreases with increasing PV system size for PV and PV+BESS installed.

With a PV system installed only, the customer draws 67.25% from the solar-generated electricity for his/her own consumption with a 1 kW PV system installed. For a 2 kW PV system installed, the customer already consumes less than half of the electricity provided with a self-consumption of 45.43%, which drops to 13.24% for a 10 kW PV system installed. As described above, the total amount of electricity self-consumed increases with increasing PV system size, but for a PV system size of 2 kW or higher most of the electricity generated is fed into the grid due to the time mismatch of electricity consumption and generation. Hence, self-consumption decreases. As expected, the self-consumption is higher with the installation of a BESS than with PV only. At a self-consumption of 96.91% for a 1 kW PV system with 5 kWh BESS installed, the customer draws and, thus, buys nearly the total share of electricity generated in year one. Up to a PV system size of 4 kW, the self-consumption exceeds 50%, which means that the total amount of electricity self-consumed is higher than the total amount of electricity fed in (cf. Figure 9 and Figure 10). However, the additional implementation of a 5 kWh BESS nearly doubles the self-consumption from 13.24% to 24.54% for a 10 kW PV system installed. For our base assumptions of a 5 kW PV system installed, the 5 kWh BESS installation raises the self-consumption from 23.41% to 45.05%. Consequently, in this setting, the third-party sells 21.64% more electricity to the customer under solar-and-storage PPAs than under solar PPAs in year one, which increases the revenue of the third-party.

In summary, the results imply that the BESS generally increases the amount of electricity self-consumed, increasing the self-sufficiency and self-consumption, and therefore can partly compensate for the time-mismatch of solar-generated electricity and residential electricity consumption[12].

4.3 Financial Analysis

4.3.1 Net present value

We examine the NPV depending on input parameters such as PV system size and initial PPA tariff to assess the financial viability of solar and solar-and-storage PPAs from the perspective of the third-party. The third-party generates revenue by either selling the electricity generated to the customer at the PPA tariff or by feeding it into the grid at the FiT. As already mentioned, we assume an initial PPA tariff of $p_0^{PPA} = \$0.24$ and distinguish between the two FiTs $p^{feedin} = \$0.0945$ and $p^{feedin} = \$0.0665$ representing the FiT benchmarks provided by IPART for 2019/20 and 2020/21, respectively. All other parameters like upfront investment costs, discount rate, escalation rate, contract duration, etc. take the values listed in Section 4.1.

NPV of solar PPAs

First, we analyse the financial viability of solar PPAs. Figure 13 displays the NPV as a function of PV system size under a solar PPA for an initial PPA tariff of $p_0^{PPA} = \$0.24$. Under the given assumptions, the investment in solar PPAs is financially viable for all PV system sizes from 1 kW to 10 kW installed for the third-party as the NPV is positive. As expected, the higher FiT in year 2019/20 results in a higher NPV than the lower FiT in year 2020/21.

For a 1 kW PV system installed, the NPV amounts to \$2078.09 and \$1954.42 for $p^{feedin} = \$0.0945$ and $p^{feedin} = \$0.0665$, respectively. For a FiT of \$0.0945, the NPV continuously increases with increasing PV system size installed up to \$5599.13 with a PV system of size 10 kW. Obviously, a larger PV system generates more electricity which is either sold to the customer or fed into the grid. Hence, when increasing the PV system size, the additional revenue generated by selling a higher

[12] Note that the solar PV system and the BESS degrade in capacity over time leading to slightly different amounts of electricity generated and charged/discharged over the years. However, the capacity degradation does not considerable change the results in a qualitative way, as both the solar PV system and the BESS degrade in capacity over the contract duration. We refer to the excel table in Appendix B for additional information about the total electricity usage over 20 years.

amount of electricity to the customer and by feeding a higher amount of electricity into the grid exceeds the higher costs of the larger PV systems.

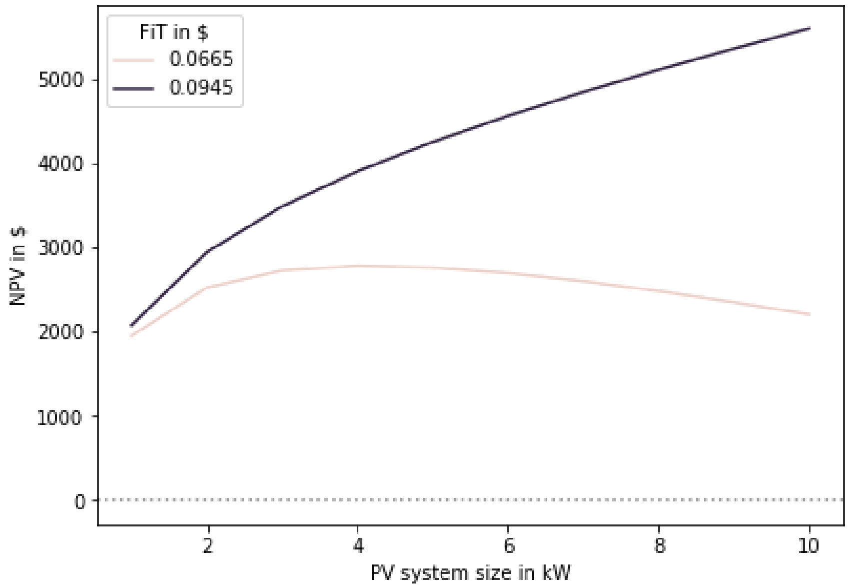

Figure 13: Net present value (NPV) under a solar PPA by Feed-in-tariff (FiT) for different PV system sizes with initial PPA tariff of $\boldsymbol{p_0^{PPA}} = \$\mathbf{0.24}$

Source: own presentation

In contrast, at the lower FiT of $p^{feedin} = \$0.0665$, the NPV rises to \$2782.74 for a 4 kW PV system installed. When the PV system size exceeds 4 kW, the NPV continuously drops to \$2206.35 with a PV system of 10 kW. This again indicates that when increasing the PV system size up to a PV system size of 4 kW, the additional revenue generated exceeds the higher costs of the PV system. Recall that the self-consumption decreases with increasing PV system size, i.e. the larger the PV system size installed, the higher is the share of electricity fed in and billed by FiT. Simultaneously, a larger PV system size leads to higher costs. The decrease of the NPV from a PV system size of 5 kW or higher indicates that a FiT of $p^{feedin} = \$0.0665$ is too low and the share of electricity fed in too high to compensate for the additional PV system costs compared to the costs of a 4 kW PV system. For 5 kW PV system size installed, the NPV amounts to \$4252.68 for $p^{feedin} = \$0.0945$, which exceeds the NPV for $p^{feedin} = \$0.0665$ at \$2762.27 by a total of \$1490.41. As already mentioned, the positive NPV under both FiTs indicates that entering into a solar PPA is financially viable for the third party. One decisive parameter in evaluating the financial viability of a PPA is its dependence on the initial PPA tariff. Therefore, we vary the initial PPA tariff in the range of $p_0^{PPA} \in \{\$0.20, \$0.21, ..., \$0.28\}$ to measure its sensitivity on the NPV.

Figure 14 illustrates the NPV as a function of PV system size per initial PPA tariff for FiT $p^{feedin} = \$0.0665$. All other parameters take the values as listed in Section 4.1. The orange dots per line indicate the PV system size at the maximum NPV per initial PPA tariff.

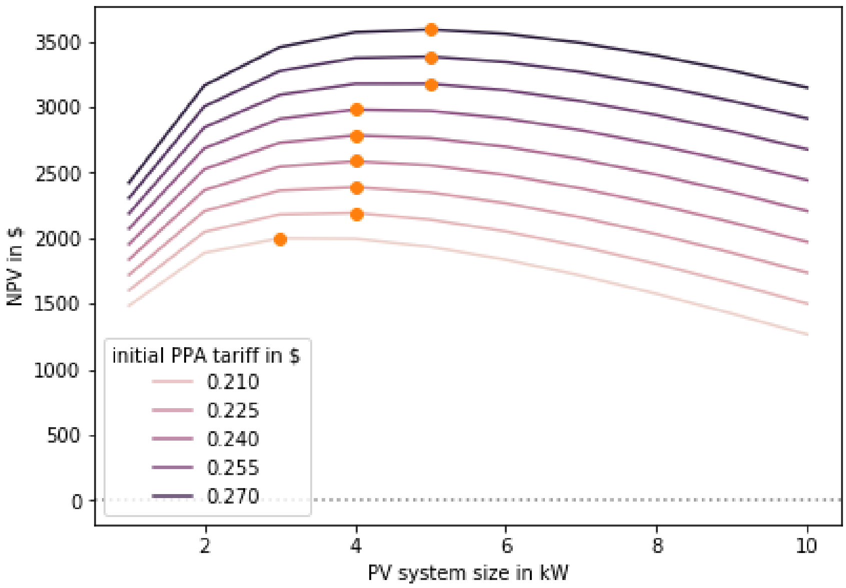

Figure 14: Net present value (NPV) under a solar PPA by initial PPA tariff for different PV system sizes with FiT of $\boldsymbol{p^{feedin}} = \$\mathbf{0.0665}$

For all initial PPA tariffs considered, the NPV shows similar behaviour as for $p_0^{PPA} = 0.24$. The NPV for each initial PPA tariff rises to a specific PV system size installed with increasing PV system size and drops beyond that.

Naturally, the NPV is higher for a higher initial PPA tariff, given a specific PV system size. A higher PPA tariff increases the revenue resulting from the amount of electricity self-consumed. Whereas entering into a solar PPA for $p_0^{PPA} = 0.20$ leads to a NPV at \$1933.79 for a 5 kW PV system size installed, the same setting with $p_0^{PPA} = 0.28$ increases the NPV by \$1656.95 to \$3590.74. Furthermore, the PV system size at the maximum NPV for each PPA tariff increases with increasing initial PPA tariff. For $p_0^{PPA} = 0.20$, the best decision is to install a 3 kW PV system resulting in a NPV of \$1999.36 and third-parties benefit most from installing a 4 kW PV systems for initial PPA tariffs between $p_0^{PPA} = 0.21$ and $p_0^{PPA} = 0.25$. If the initial PPA tariff is in the range of $p_0^{PPA} = 0.26$ to $p_0^{PPA} = 0.28$, a 5 kW PV system maximises the NPV. Hence, our results indicate that a higher initial PPA tariff motivates the third-party to install a larger PV system under solar PPAs.

Figure 15 presents the NPV as a function of PV system size per initial PPA tariff for FiT $p^{feedin} = \$0.0945$. Similar to $p^{feedin} = \$0.0665$, the NPV rises with increasing initial PPA tariff given a specific PV system size. However, the NPV is higher for larger PV system sizes installed for each initial PPA tariff. Thus, from a third-party perspective, the investment in solar PPAs is more economically beneficial when installing large PV systems than small systems.

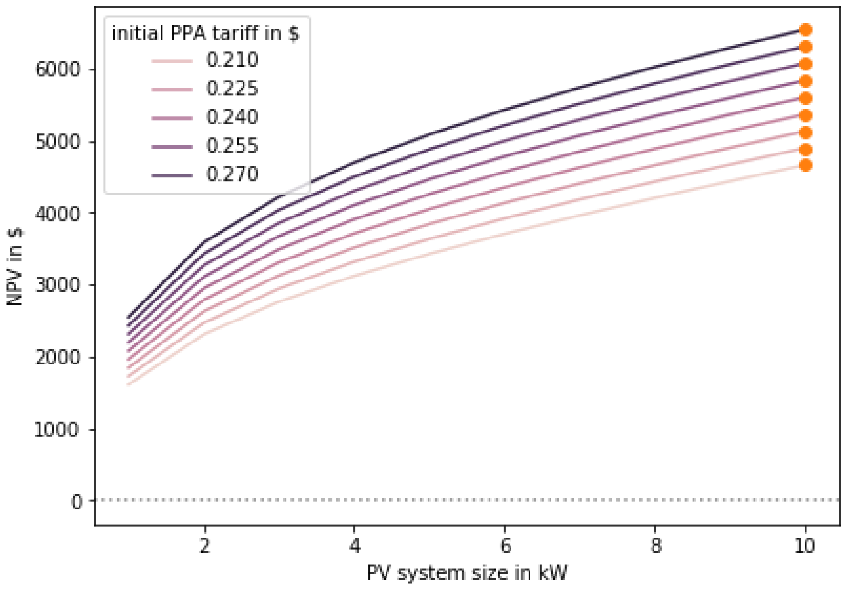

Figure 15: Net present value (NPV) under a solar PPA by initial PPA tariff for different PV system sizes with FiT of $\boldsymbol{p^{feedin}} = \$\mathbf{0.0945}$

NPV of solar-and-storage PPAs

This section examines the financial impact of a 5 kWh BESS installation on the financial viability of solar PPAs. In the following, we present the NPV of solar-and-storage PPAs under the base case scenario. In this context, Figure 16 illustrates the NPV as a function of PV system size under a solar-and-storage PPA with a BESS of size 5 kWh installed.

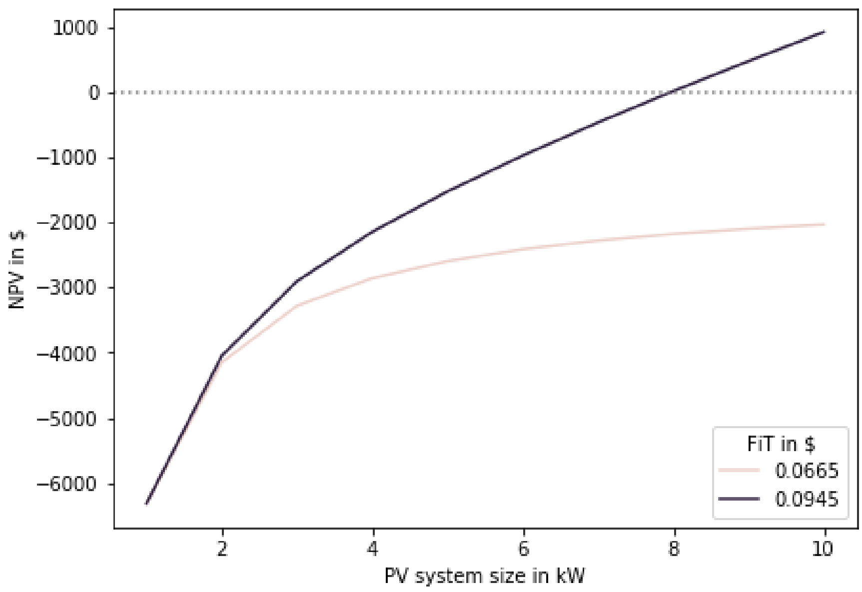

Figure 16. Net present value (NPV) under a solar-and-storage PPA with a 5 kWh BESS installed by Feed-in-tariff (FiT) for different PV system sizes with initial PPA tariff of $\boldsymbol{p_0^{PPA}} = \$\mathbf{0.24}$

Like in solar PPAs, the higher FiT in year 2019/20 results in a higher NPV than the lower FiT in year 2020/21. For a 5 kW PV system installed, the NPV amounts to -$1527.09 for $p^{feedin} = \$0.0945$ exceeding the NPV for $p^{feedin} = \$0.0665$ at -$2596.30 by a total of $1069.21. The negative NPV in both settings indicates that entering into a solar-and-storage PPA with 5 kWh BESS storage size installed is not financially viable for the third-party. Under current assumptions, a BESS of 5 kWh increases the self-consumption on average by 19.15% for a 5 kW PV system installed over 20 years (see *Appendix B*). Consequently, the revenue resulting from the increase in self-consumption cannot compensate for the costs related to the BESS.

However, the NPV increases with increasing PV system size installed for both FiTs. For $p^{feedin} = \$0.0945$, an investment in solar-and-storage PPAs becomes economically beneficial for a PV system of size 8 kW or larger, i.e. the third-party benefits from a NPV of $918.72 with 10 kW installed. In contrast for $p^{feedin} = \$0.0665$, the investment in solar-and-storage PPAs with a 5 kWh BESS installed remains not financially viable for all PV system sizes considered. For a PV system of 10 kW installed, the third-party expects a NPV amounting to -$2035.32 and would therefore decide not to invest in solar-and-storage PPAs.

Again, we consider the sensitivity of the initial PPA tariff on the financial viability of solar-and-storage PPAs. Figure 17 illustrates the NPV for a 5 kWh BESS size as a function of PV system size per initial PPA tariff $p_0^{PPA} \in \{\$0.20, \$0.21, ..., \$0.28\}$ for a FiT of $\$0.0665$.

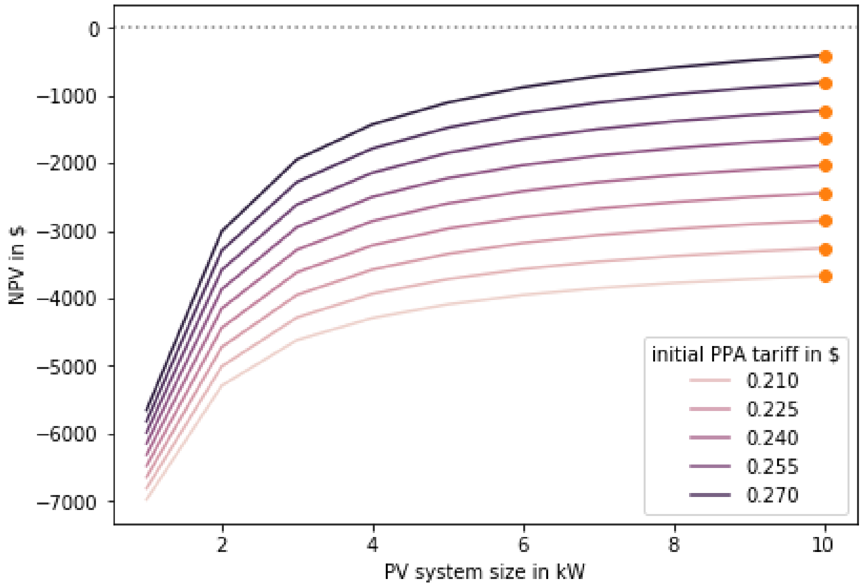

Figure 17: Net present value (NPV) under a solar-and-storage PPA with a 5 kWh BESS installed by initial PPA tariff for different PV system sizes with FiT of $\boldsymbol{p^{feedin}} = \$\mathbf{0.0665}$

As expected, the NPV for all initial PPA tariffs considered displays the same behaviour as for $p_0^{PPA} = 0.24$, and a higher initial PPA tariff leads to a higher NPV. For 5 kW PV system size installed an initial PPA tariff of $p_0^{PPA} = 0.20$ results in a NPV of -$4088.78. The same setting with $p_0^{PPA} = 0.28$ results in a NPV of -$1103.82, which amounts to a surplus of $2984.96 compared to the NPV at $p_0^{PPA} = 0.20$. Nevertheless, from a third-party perspective, entering into a solar-and-storage PPA remains not financially viable for 5 kWh BESS size installed for all initial PPA tariffs in the range of $0.20 to $0.28, and all PV systems sizes between 1 kW and 10 kW installed. However, for each PPA tariff considered, the results indicate a larger PV system at maximum NPV under solar-and-storage PPAs than under solar PPAs (orange dots). For all initial PPA tariffs from $0.20 to $0.28, the best decision is to invest in a PV system of size 10 kW for a 5 kWh BESS installed. This effect can be linked to the higher self-consumption due to the BESS implementation. The additional revenue resulting from the increase in self-consumption due to BESS installation, which is billed by the PPA tariff, is high enough to cover the costs of larger PV systems. However, the installation of a 5 kWh BESS under a PPA is not economically beneficial for the third-party with current assumptions. The results show that installing a larger PV system size is always more economically beneficial with a 5 kWh BESS installed.

Figure 18 displays the NPV for a 5 kWh BESS size as a function of PV system size per initial PPA tariff $p_0^{PPA} \in \{\$0.20, \$0.21, ..., \$0.28\}$ for a higher FiT of $\$0.0945$. Again, the NPV rises with increasing initial PPA tariff. As expected, the higher FiT of $\$0.0945$ results in a higher NPV per initial PPA tariff than the FiT of $\$0.0665$ for each PV systems size, making the investment in solar-and-storage PPAs financial viable for large PV systems installed and high initial PPA tariffs.

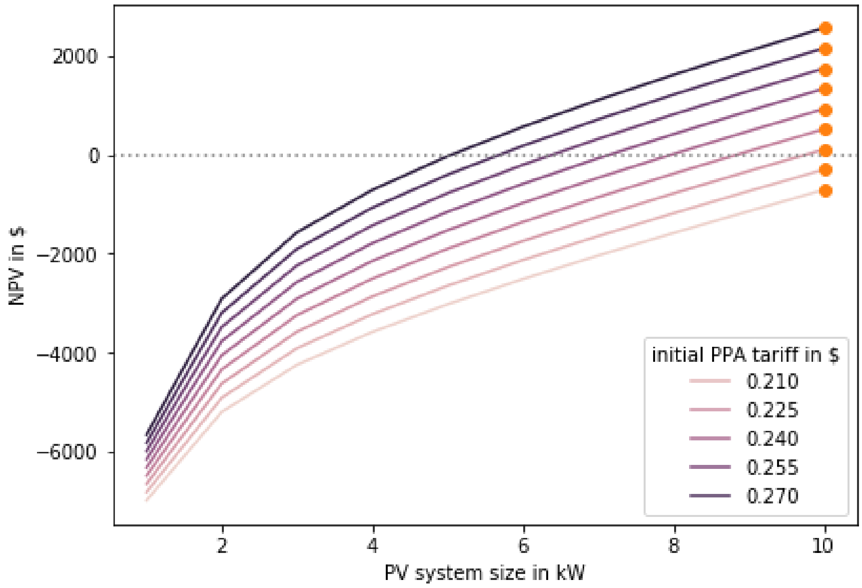

Figure 18: Net present value (NPV) under a solar-and-storage PPA with a 5 kWh BESS installed by initial PPA tariff for different PV system sizes with FiT of $\boldsymbol{p^{feedin}} = \$\mathbf{0.0945}$

Electricity bill savings

This section presents the electricity bill savings of the customer under solar and solar-and-storage PPAs under the base case scenario. Figure 19 illustrates the electricity bill savings of the customer under a solar and solar-and-storage PPA as present value depending on the PV system size for flat-rate (left) and TOU customers (right). Again, a 5 kWh BESS is installed under the solar-and-storage PPA.

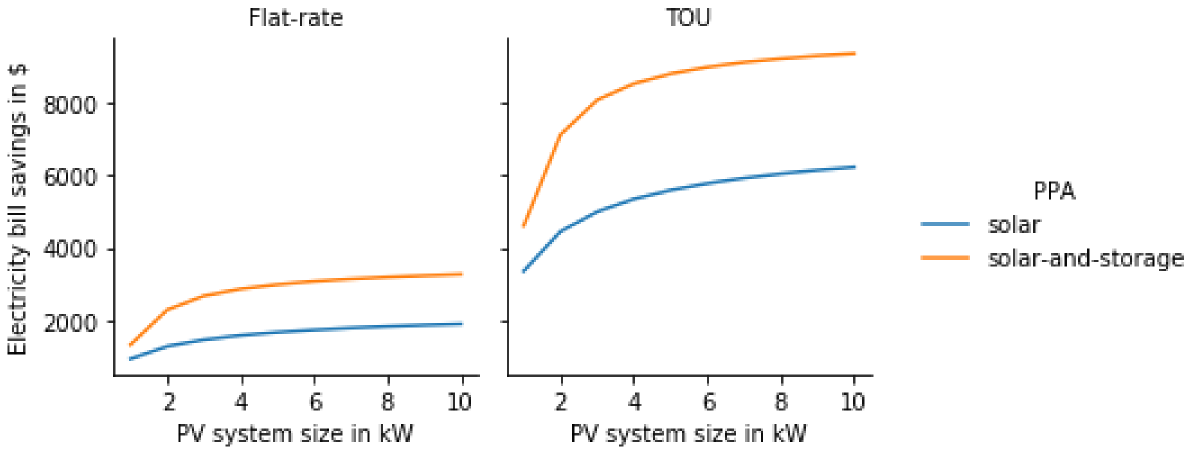

Figure 19: Electricity bill savings for flat-rate (left) and TOU customers (right) under a solar PPA (blue line) and solar-and-storage PPA (orange line) with a 5 kWh BESS installed for different PV system sizes

Under solar PPAs, the electricity bill savings of the customer increase with increasing PV system size installed for both flat-rate and TOU customers. By entering into a solar PPA (blue line), flat-rate customers save $1678.87 for 5 kW PV system size installed. For the same PV system size installed, the electricity bill savings of TOU customers are at $5591.36, i.e. more than three times higher. Installing a PV system of size 1 kW results in a decrease in electricity bill saving to $947.23 for flat-rate and $3361.47 for TOU customers. However, a PV system size of 10 kW results in electricity bill savings of $1907.41 for flat-rate and $6226.13 for TOU customers.

Under solar-and-storage PPAs, the electricity bill savings of the customer also increase with increasing PV system size installed for both flat-rate and TOU customers. A 1 kW PV system leads to electricity bill savings of $1333.92 for flat-rate and $4611.67 for TOU customers and a 10 kW PV system to $3273.50 for flat-rate and $$9348.43 for TOU customers. However, under both solar and solar-and-storage PPAs, the increase in electricity bill savings with increasing PV system size decreases, reflecting the curve shape of self-sufficiency for PV and PV+BESS with increasing PV system size, respectively.

As expected, solar-and-storage PPAs result in higher electricity bill savings than solar PPAs for both flat-rate and TOU customers. By entering into a solar-and-storage PPA with 5 kWh BESS capacity installed, flat-rate customers save $2992.16 and TOU customers save $8791.36 for a 5 kW PV system installed. Thus, the 5 kWh BESS increases the electricity bill savings of flat-rate customers by 78.23% and of TOU customers by 57.23%, compared to the electricity bill savings under a solar PPA. This increase can be attributed to the higher self-sufficiency due to BESS installation. The increase in electricity bill savings when adding a 5 kWh BESS remains almost stable for all PV system sizes larger than 4 kW for both flat-rate and TOU customers. For example, for a 10 kW PV system installed, the electricity bill savings increase by 71.62% for flat-rate customers and by 50.15% for TOU customers. This effect results from the utilization of the BESS, as a 5 kWh BESS is nearly fully utilized with a 4 kW PV system installed and a larger PV system size increases the amount of electricity stored only marginally. Nevertheless, for a 1 kW PV system installed, the increase is lower, with 40.82% and 37.19% for flat-rate and TOU customers, respectively.

Overall, these results imply that the reduction in the electricity bill of the customer under both solar and solar-and-storage PPAs is higher for TOU customers than for flat-rate customers. Flat-rate customers save for each kWh electricity self-consumed the same money independently of the daytime. For example, in year one, solar and solar-and-storage PPAs reduces the electricity bill of the customer by \$0.0552 per kWh electricity self-consumed at a flat-rate tariff of \$0.2952 and an initial PPA tariff of \$0.24. In contrast, TOU customers save the most money when drawing the solar-generated electricity during peak hours between 2 pm and 8 pm on business days at the highest TOU tariff valid. Also, they profit marginally from the electricity self-consumed at shoulder hours. Only during off-peak hours, the TOU tariff is below the PPA tariff. Nevertheless, the savings during peak and shoulder hours are high enough to compensate for the negative impact on electricity bill savings at off-peak times. For example, during the first contract year, TOU customer save \$0.3045 per kWh electricity self-consumed between 2 pm and 8 pm at a TOU tariff of \$0.5445 per kWh with an initial PPA tariff of 0.24. Contrary, they make a loss of \$0.0425 per kWh self-consumed during off-peak periods. The installation of a BESS mainly increases the amount of electricity self-consumed at peak hours, as the BESS discharges most of its electricity stored from 3 pm to the evening hours. Consequently, TOU customers extremely profit from the high spread between PPA tariff and TOU tariff, as they can cover their evening consumption peak with the electricity supplied from the BESS. Although both flat-rate and TOU customer benefit from positive electricity bill savings when entering into a solar PPA, we find that flat-rate customers have a low incentive to do so, as the net electricity bill savings over 20 years are rather small. However, BESS installations increase the electricity bill savings for both flat-rate and TOU customers, making the financing of PV+BESS under a solar-and-storage PPA, especially for TOU customers, economically very beneficial.

Furthermore, we want to examine the impact of different initial PPA tariffs on the electricity bill savings of the customer under both solar and solar-and-storage PPAs. Figure 20 depicts the electricity bill savings under solar PPAs for flat-rate and TOU customers depending on PV system size for initial PPA tariffs in the range of $p_0^{PPA} \in \{\$0.20, \$0.21, \ldots, \$0.28\}$. Overall, the electricity bill savings are higher with lower initial PPA tariffs. For a 5 kW PV system installed, customers with flat-rate tariffs save \$2895.43 at $p_0^{PPA} = \$0.20$ and \$462.30 at $p_0^{PPA} = \$0.28$, and TOU customers save \$6807.93 at $p_0^{PPA} = \$0.20$ and \$4374.79 at $p_0^{PPA} = \$0.28$ under base-case assumptions. However, the increase of electricity bill savings with increasing PV system size flattens beyond a specific size of the PV system installed for each PPA tariff considered, which is again due to the lower self-sufficiency growth with increasing PV system size. For flat-rate customers, the incentive to invest in solar PPAs is low for initial PPA tariffs exceeding $p_0^{PPA} = \$0.24$. Their net savings on the electricity bill over 20 years amounts to a maximum of \$1561.86 at $p_0^{PPA} = \$0.25$ for a PV system capacity of 10 kW installed and to a minimum of \$ 260.83 with $p_0^{PPA} = \$0.28$ for a 1 kW PV system installed. However, flat-rate customers save \$3289.59 at an initial PPA tariff of $p_0^{PPA} = \$0.20$ having a 10 kW PV system installed. In contrast, the electricity bill savings of TOU customers are relatively high for all initial PPA tariffs considered. TOU customers save a minimum of \$ 2675.07 for a 1 kW PV system installed with $p_0^{PPA} = \$0.28$ and a maximum of \$7608.31 for a 10 kW PV system installed with $p_0^{PPA} = \$0.20$ under solar PPAs.

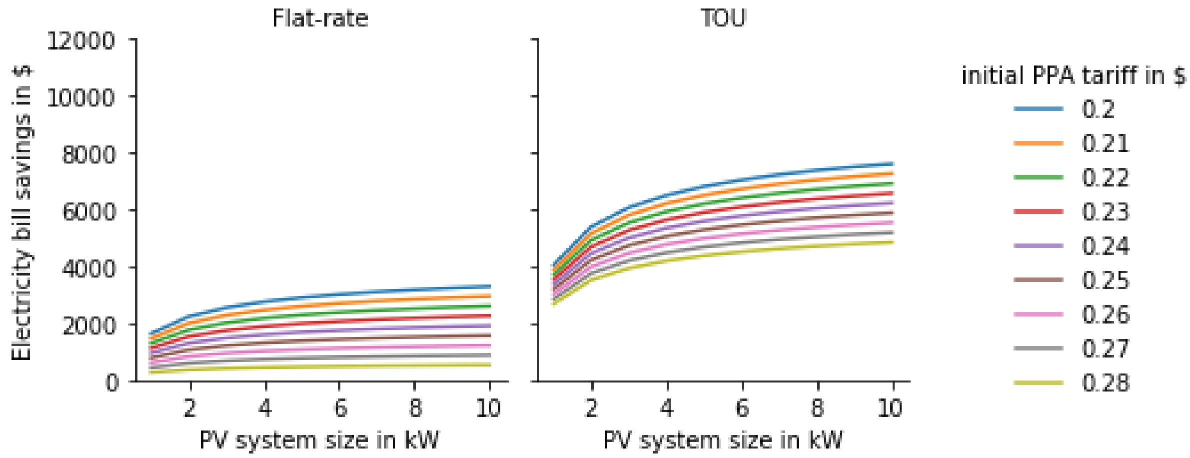

Figure 20: Electricity bill savings for flat-rate (left) and TOU customers (right) under a solar PPA by initial PPA tariff for different PV system sizes

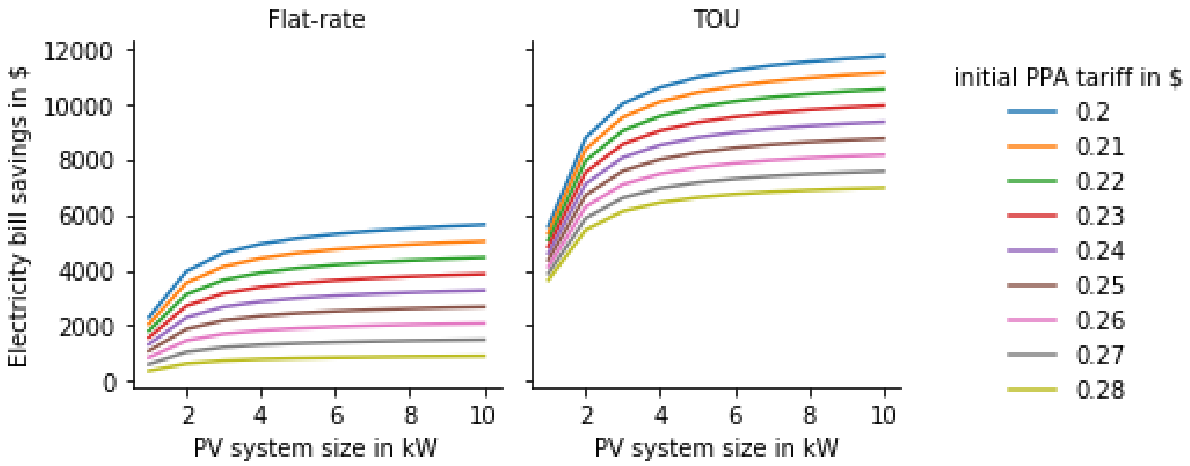

Figure 21: Electricity bill savings for flat-rate (left) and TOU customers (right) under a solar-and-storage PPA with a 5 kWh BESS installed by initial PPA tariff for different PV system sizes

Similar to Figure 20, Figure 21 illustrates the electricity bill savings for different initial PPA tariffs depending on PV system size for flat-rate and TOU customers under solar-and-storage PPA with a 5 kWh BESS size installed.

Again, the electricity bill savings decrease with increasing initial PPA tariff and exceed those of a solar PPA. For 5 kW PV system size installed, the net savings amount to \$5160.39 and \$10959.59 at $p_0^{PPA} = \$0.20$ and decrease to \$823.93 and \$6623.13 at $p_0^{PPA} = \$0.28$ for flat-rate and TOU customers, respectively. Hence, adding a 5 kWh BESS to the 5 kW PV system installed leads to an increase of 78.23% (78.23%) for flat-rate and 60.98% (51.39%)[13] for TOU customers at $p_0^{PPA} =$

[13] Note that the percentual increase of electricity bill savings for flat-rate customers due to BESS installation is independent of the initial PPA tariff, as the electricity is billed independently of time. However, the BESS shifts the electricity generated to different daytimes resulting in different electricity bill savings per time dependent on the PPA tariff explaining the lower percentual increase in electricity bill savings for TOU customers with a higher initial PPA tariff.

\$0.20 ($p_0^{PPA} = \$0.28$). Nevertheless, TOU customer save \$11720.53 with a 10 kW PV system installed at $p_0^{PPA} = \$0.20$ and \$3645.07 with a 1 kW PV system installed at $p_0^{PPA} = \$0.28$. The net savings of flat-rate customers are lower with \$5645.60 for a 10 kW PV system installed with $p_0^{PPA} = \$0.20$ and \$367.31 for a 1 kW PV system installed with $p_0^{PPA} = \$0.28$

Comparing Figure 20 and Figure 21 shows that entering into a solar-and-storage PPA is more economically beneficial than entering into a solar PPA for both flat-rate and TOU customers at each initial PPA tariff for each PV system size installed.

4.4 Sensitivity Analysis

A comprehensive overview of the financial viability for solar and solar-and-storage PPAs is crucial to support both the third-party and the customer in deciding whether to invest in solar and solar-and-storage PPAs, respectively. In the following, we vary the parameters fixed in the base case scenario like BESS size, PV and BESS costs, and the contract duration, measuring their impact on the technical metrics self-sufficiency and self-consumption and the financial metrics NPV and electricity bill savings.

Battery Energy Storage System size

As mentioned in Section **Error! Reference source not found.**, the BESS size selection is decisive in evaluating solar-and-storage PPAs. Therefore, we consider BESSs of size 3 kWh, 5 kWh, 8 kWh, 10 kWh and 15 kWh and show their technical effect on the amount of electricity stored, the self-sufficiency and the self-consumption in year one of the PPA. Subsequently, we analyse the financial impact of the different BESS sizes on the NPV and the electricity bill savings. The results shown in this section are calculated based on the technical and financial input parameters listed in Section 4.1. [14]

Impact on self-sufficiency and self-consumption

Figure 22 depicts the amount of electricity stored for different BESS sizes as a function of PV system size in year one of the PPA.

[14] Note that we only vary the size of the BESS system and keep the technical characteristics such as (dis-)charging rate and round trip efficiency as for a 5 kWh BESS installed.

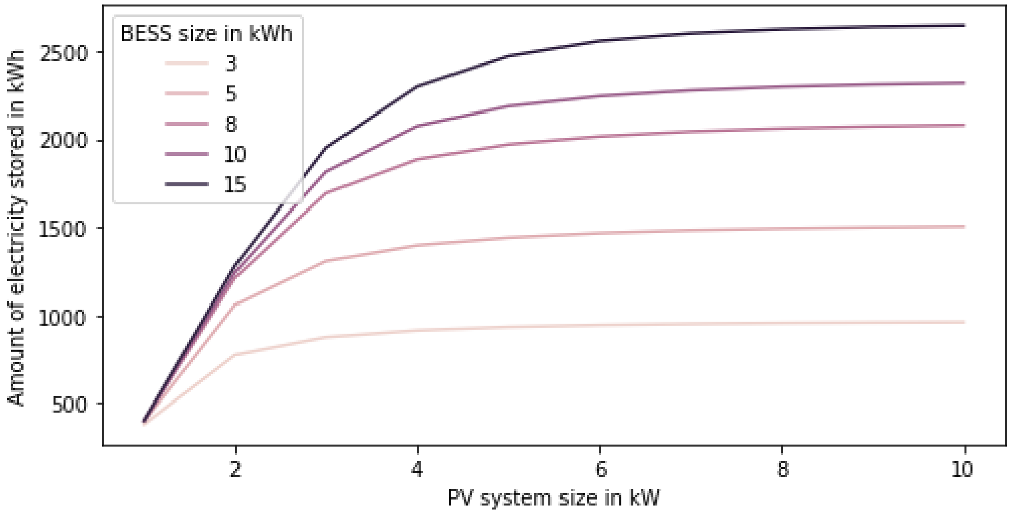

Figure 22: Amount of electricity stored under solar-and-storage PPAs for different BESS sizes and PV system sizes installed in year one

As expected, a larger BESS size installed leads to a higher amount of electricity stored for each PV system size installed. For example, with a PV system size of 5 kW, a 3 kWh BESS stores 932.60 kWh, an 8 kWh BESS 1969.54 kWh and a 15 kWh BESS 2472.42 kWh in year one. The amount of electricity stored per BESS size increases with an increasing PV system size. For each BESS size, the amount of electricity stored rises rapidly with larger PV system size up to a specific PV system size, from which the ratio of increase decreases. This specific PV system size is again higher for larger BESSs installed and indicates the PV system size for which the BESS is nearly fully utilised. A BESS with a capacity of 3 kWh is nearly fully utilised at a 3 kW PV system installed and a BESS with a size of 10 kWh at a 7 kW PV system. Furthermore, the amount of electricity stored at a 1 kW PV system size installed is almost the same for each BESS size considered. A PV system of size 1 kW provides such a low amount of electricity that even a BESS of 3 kWh stores almost all the electricity generated remaining after the electricity consumption of the customer.

However, the increase in additional electricity stored due to a larger BESS size seems to decrease with increasing BESS size for a certain PV system size. Whereas a 5 kWh BESS stores 507.70 kWh more than a 3 kWh BESS, the additional amount of electricity stored when adding 2 kWh to an 8 kWh BESS amounts to 218.14 kWh for a 5 kW PV system installed. The State of Charge[15] analysis per BESS size shows that for each BESS size installed, the BESS is, on average, almost fully loaded once per day for PV systems above a specific size. But the average minimum SoC reached per day increases with a larger BESS size. Two reasons can explain this BESS cycling behaviour. Firstly, the discharging rate limits the electricity output of the BESS for customers with high daily electricity consumption during the evening peak hours. Note that the discharging rate is assumed to be 5 kWh for all BESS sizes installed, also reflecting the discharging rate of larger BESSs available in Australia (SolarQuotes, 2021). Secondly, some customers' daily electricity consumption is too low to discharge the larger BESSs fully. However, the high average minimum SoC prevents larger BESSs from charging more electricity.

[15] The SoC per BESS size is depicted in Appendix C.

Self-sufficiency

The size of the BESS installed influences the self-sufficiency of the customer, which Figure 23 graphically illustrates for year one. For a given PV system size, the self-sufficiency increases with increasing BESS size installed. For example, at a PV system size of 5 kW, 51.24% of the customer's total electricity consumption in year one is covered by the PV+BESS with a 3 kWh BESS installed and 82.77% with a 15 kWh BESS installed. This is no surprise, as a larger BESS stores more electricity, and the customer can cover a higher share of her/his electricity consumption with the solar-generated electricity provided by the BESS.

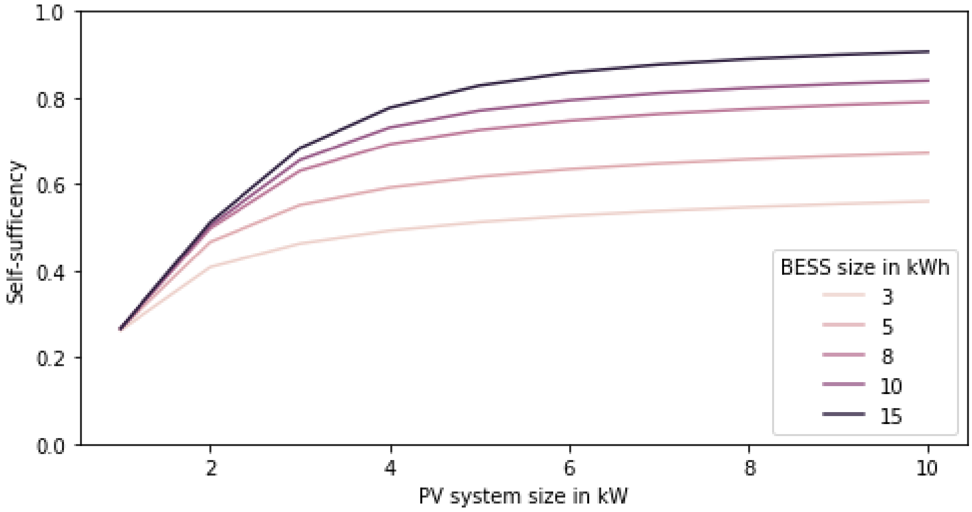

Figure 23: Self-sufficiency under solar-and-storage PPAs for different BESS sizes and PV system sizes installed in year one

Nevertheless, the increase in self-sufficiency for larger BESSs installed decreases with increasing BESS size. Adding 2 kWh to a 3 kWh BESS increases the self-sufficiency by 10.43%, and adding the same capacity to an 8 kWh BESS raises the self-sufficiency by 4.46%. This effect can be directly linked to the curve shape of the electricity stored per year, as with a higher BESS size, the additional amount of electricity stored decreases.

For each BESS size, the customer covers a higher share of her/his annual electricity consumption if a larger PV system size is installed. Again, the self-sufficiency curve per BESS capacity flattens beyond a specific PV system size, since the BESS is nearly fully utilised with this specific PV system size installed (cf. SoC per BESS size in *Appendix D*). For a 10 kWh BESS installed, the BESS is nearly fully utilised with a PV system size of 7 kW at a self-sufficiency of 81.02%. With a larger PV system size, the BESS can only redistribute a small additional amount of electricity to meet the demand of the customer. Increasing the PV system size of 7 kW by 3 kW leads to an increase in the self-sufficiency of 83.90% for a 10 kWh BESS installed within year one.

Self-consumption

For each PV system size installed, the self-consumption is higher with a larger BESS installed, as displayed in Figure 24. The customer consumes at a self-consumption of 37.43%, less than half of the electricity generated by a 5 kW PV system, for a 3 kWh BESS installed in year one, but nearly

60.46% of the same amount of electricity generated for a 15 kWh BESS. Again, this could be expected as the amount of electricity stored is higher for larger BESSs installed.

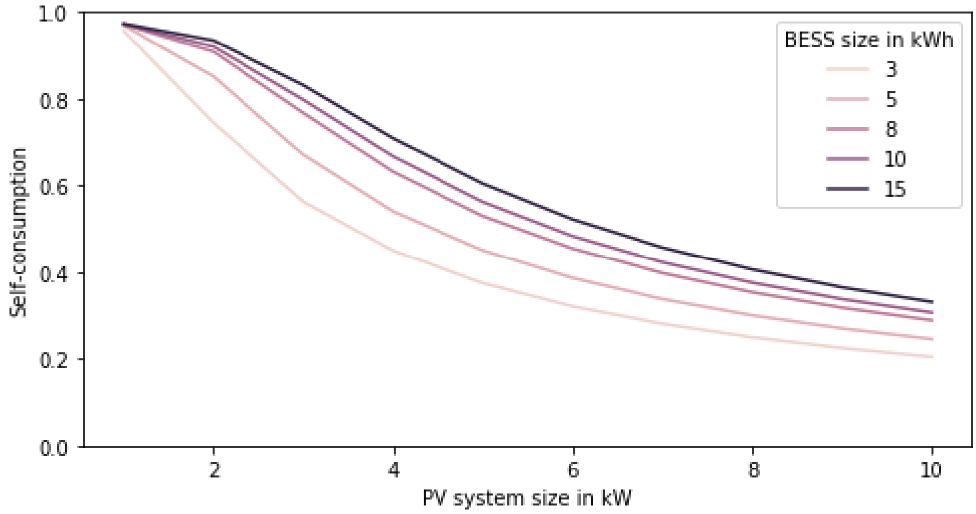

Figure 24: Self-consumption under solar-and-storage PPAs for different BESS sizes and PV system sizes installed

Furthermore, the increase in self-consumption decreases with increasing BESS size installed, reflecting the curve shape of the amount of electricity stored. For example, for a 5 kW PV system installed, 7.62% more of the electricity generated is self-consumed by the customer when a BESS of size 5 kWh instead of 3 kWh is installed and 3.26% more when a 10 kWh BESS instead of an 8 kWh BESS is installed.

For each BESS size installed, the self-consumption decreases with increasing PV system size. For example, with a 15 kWh BESS installed, almost all of the electricity generated is self-consumed at a self-consumption of 97.20% for a 1 kW PV system installed. In contrast, the main part of the electricity generated is fed into the grid at a self-consumption of 33.08% for a 10 kW PV system installed.

Impact on Net present value

We measure the impact of different BESS sizes on the NPV of solar-and-storage PPAs under the base case scenario for a 5 kW PV system installed at an initial PPA tariff of $p_0^{PPA} = \$0.24$, applying both FiT benchmarks as displayed in Figure 25. Note that the bars in Figure 25 with BESS size in kWh equal to zero represent the solar PPA case without storage implementation.

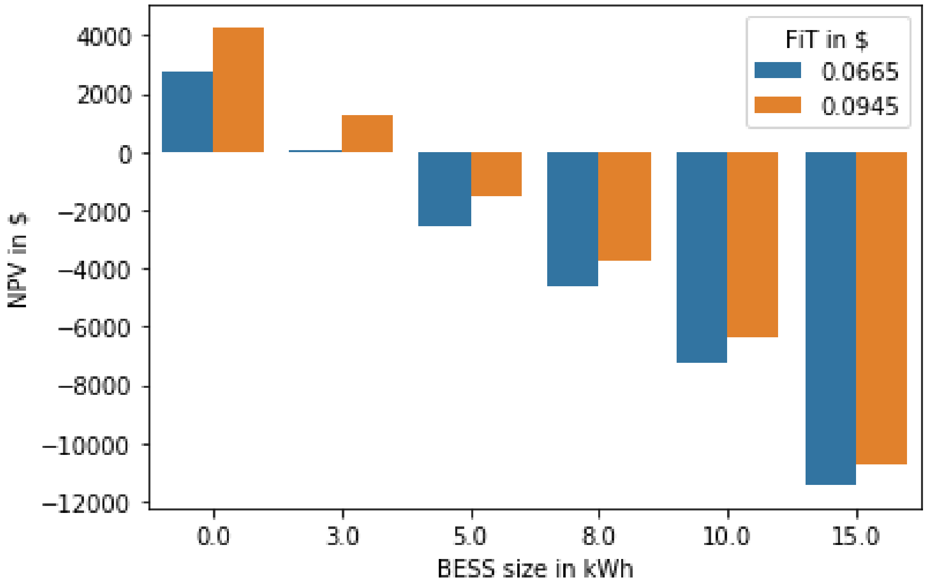

Figure 25: Net Present Value (NPV) by Feed-in Tariff (FiT) under a solar PPA (left bars) and solar-and-storage PPAs for different BESS sizes with a 5 kW PV system installed with initial PPA price $\boldsymbol{p_0^{PPA}} = \$\mathbf{0.24}$

For both FiTs, the NPV of solar-and-storage PPAs decreases with increasing BESS size. Hence, the additional revenue, resulting from the increased self-consumption due to the battery storage installation, does not cover the total additional initial installation and O&M costs of the BESS for each BESS size installed. Only for a BESS size of 3 kWh installed the revenue from the BESS installation is sufficient to result in a positive NPV for solar-and-storage PPAs at both FiTs. For a 3 kWh BESS installed, the third-party financially profits from a NPV of $51.23 at $p^{feedin} = 0.0665$ and of $1273.34 at $p^{feedin} = 0.0945$. Again, the NPV at the higher FiT exceeds the one with the lower FiT for each BESS size installed, as the revenue resulting from the share of electricity fed into the grid and billed by FiT is higher with a higher FiT. For example, for a 15 kWh BESS installed, the NPV amounts to -$11446.97 at $p^{feedin} = 0.0665$ and -$10747.32 at $p^{feedin} = 0.0945$. In summary, we conclude that installing a PV+BESS instead of a PV system stand-alone decreases the financial viability of PPAs for the third-party. Although entering into a solar-and-storage PPA with a 3 kWh BESS results in a positive NPV, the third-party would prioritize installing a PV system stand-alone under a solar PPA, as this investment has a higher NPV. *Appendix E* provides more information about the NPV depending on the PV system size for each BESS size considered.

Electricity bill savings

The electricity bill savings of customers entering into a solar-and-storage PPA with a 5 kW PV system at an initial PPA tariff of $p_0^{PPA} = \$0.24$ for different sizes of the BESS installed are depicted in Figure 26. Again, we distinguish between flat-rate and TOU customers.

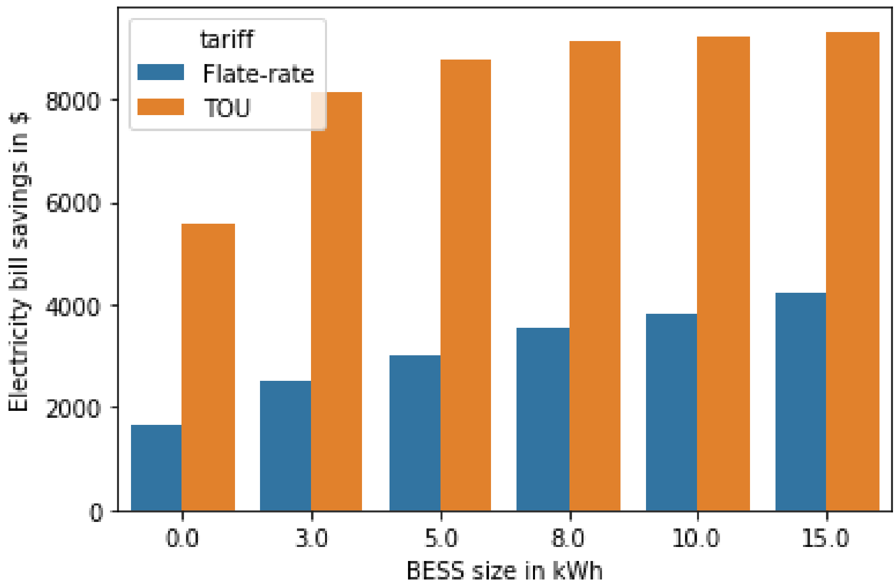

Figure 26: Electricity bill savings for flat-rate and TOU customers under a solar PPA (left bars) and solar-and-storage PPAs for different BESS sizes with a 5 kW PV system installed

As expected, the electricity bill savings are higher with a larger BESS installed. Customers profit from the higher self-sufficiency (cf. Figure 23) and do not have to afford the additional costs of the BESS. However, the increase in electricity bill savings decreases with increasing BESS size installed, reflecting the curve of self-sufficiency with increasing BESS size. For a 5 kW PV system installed, flat rate customers can reduce their electricity bill by $2511.76 with a 3 kWh BESS, by $3559.07 with an 8 kWh BESS and by $4212.21 with a 15 kWh BESS. However, a BESS size beyond 8 kWh only marginally raises the electricity bill savings for TOU customers. TOU customers save $8133.35 having a 3 kWh BESS and $9126.44 having an 8 kWh BESS installed, which differs only by $195.81 from the electricity bill savings having a 15 kWh BESS installed. For larger BESSs installed, the customers draw a higher share of the electricity stored at night times, where the TOU tariff is below the PPA tariff. Nevertheless, customers save enough money at peak times to compensate for the negative impact on electricity bill savings at off-peak times.

Investment costs

Further sensitive parameters in the financial evaluation of PPAs are the investment costs for the PV system and the BESS, respectively. Solar-and-storage PPAs may become financially viable for the third-party in the following years, as costs for battery storage are expected to decline significantly in the future (International Renewable Energy Agency, 2017; Nykvist and Nilsson, 2015). Figure 27 provides an overview of the NPV for a 5 kW PV system and 5 kWh BESS installed depending on both PV system and BESS investment costs with our base assumptions at $p_0^{PPA} = \$0.24$ and $p^{feedin} = \$0.0665$. Therefore, we assume upfront investment costs of the PV system between $500 and $1050 per kW installed and upfront investment costs of the BESS between $800 and $1450 per kWh capacity installed (in steps of $50). The O&M costs of the PV system amount to 1.5% of the PV system investment costs and the O&M costs of the BESS remain constant, as those depend on the BESS size installed.

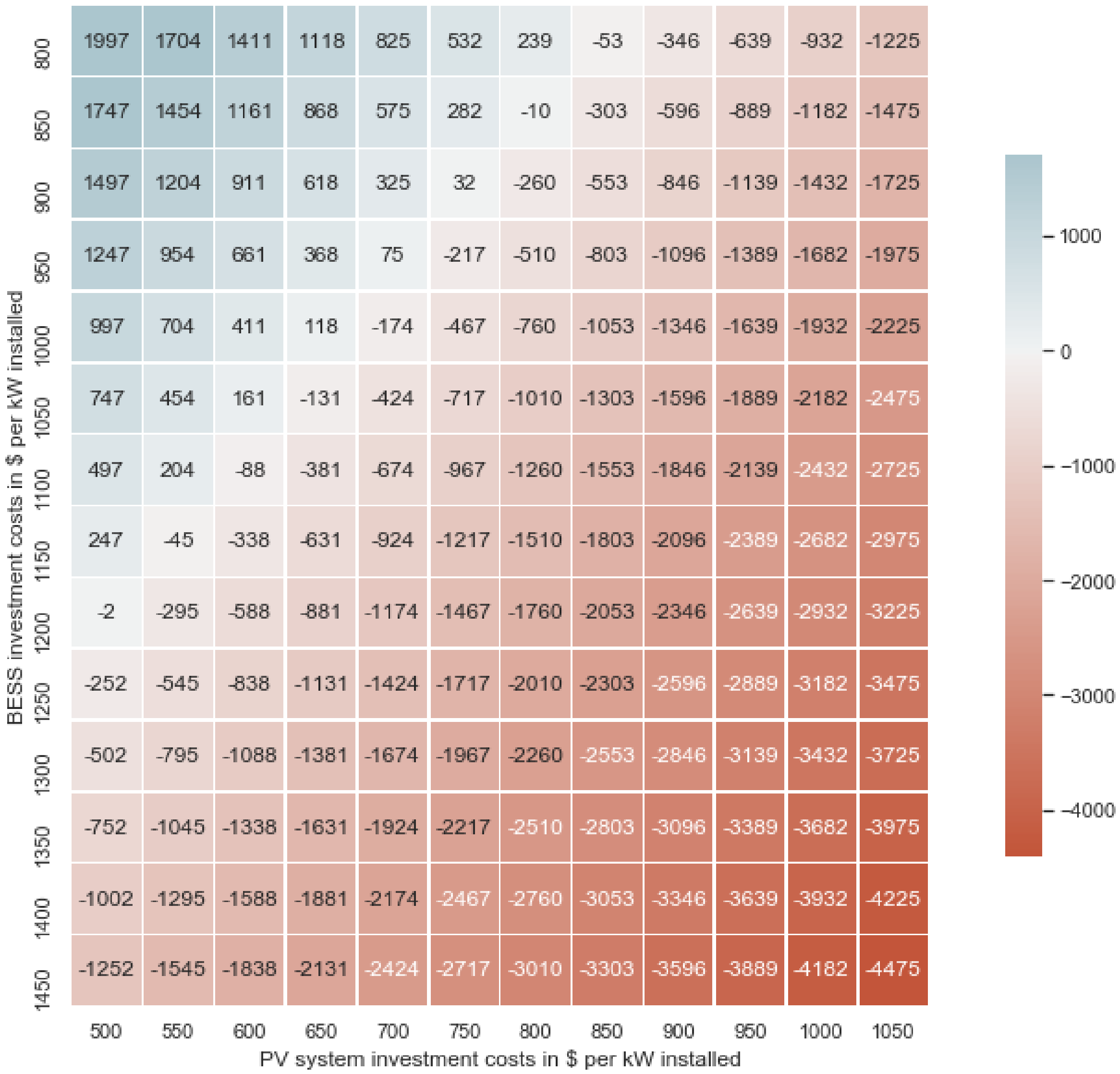

Figure 27: Net Present Value (NPV) under solar-and-storage PPA with a 5 kW PV system and 5 kWh BESS installed for different PV system investment costs (x-axis) and BESS investment costs (y-axis) with initial PPA tariff $\boldsymbol{p_0^{PPA} = \$0.24}$ at FiT $\boldsymbol{p^{feedin} = 0.0655}$

As expected, the NPV decreases with increasing PV system investment costs and BESS investment costs, respectively. With PV system investment costs of $1050 per kW installed and BESS investment costs of $1450 per kWh installed, the NPV amounts to -$4475. In this setting, a third-party would not invest in solar-and-storage PPAs with 5 kW PV and 5 kWh BESS installed, respectively. However, Figure 27 shows that the NPV is positive in most cases when the overall investment costs of the PV system and the BESS are equal or less than $1650. For example, for PV system investment costs of $650 per kW installed and BESS investment costs of $1000 per kWh installed, the investment in solar-and-storage PPAs is economically beneficial for the third party resulting in a NPV of $119. Nevertheless, the incentive to do so is relatively low. With assumed costs of $500 per kW PV system size installed and $800 per kWh BESS size installed, third-parties can benefit from a higher NPV of $1997.

Figure 28 displays the NPV for a 5 kW PV system and 5 kWh BESS installed depending on both PV system and BESS investment costs under the base case scenario at $p_0^{PPA} = \$0.24$ and $p^{feedin} = \$0.0945$. The higher FiT makes the investment in solar-and-storage PPA financially viable for higher overall investment costs of the PV system and the BESS. In most cases, overall investment costs up to $1850 lead to a positive net profit for the third-party.

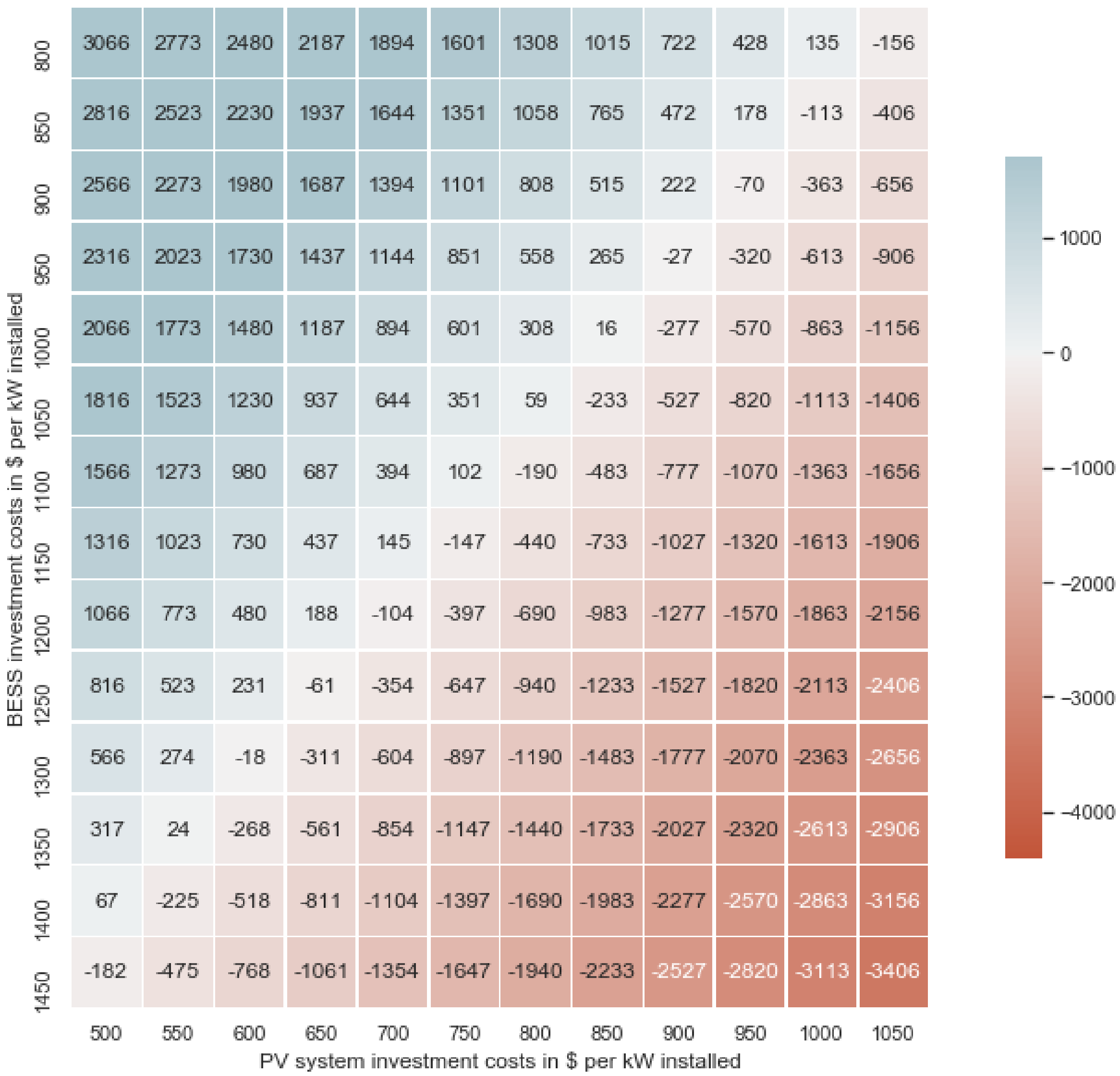

Figure 28: Net Present Value (NPV) under solar-and-storage PPA with a 5 kW PV system and 5 kWh BESS installed for different PV system investment costs (x-axis) and BESS investment costs (y-axis) with initial PPA tariff $\boldsymbol{p_0^{PPA}} = \$\mathbf{0.24}$ at FiT $\boldsymbol{p^{feedin}} = \mathbf{0.0945}$

Contract duration

As already mentioned in Section **Error! Reference source not found.**, the duration of the PPA contract is prefixed and typically varies between 15 and 20 years. When entering into a solar and solar-and-storage PPA, a shorter contract duration will result in lower electricity bill savings for the customer, as less electricity is self-consumed. Nevertheless, the electricity bill savings of the customer will stay positive for each contract duration as displayed in *Appendix F*. In contrast, the impact of the PPA duration on the financial viability of solar and solar-and-storage PPAs for the third-party is not clear in advance.

Solar PPAs

Figure 29 shows the NPV as a function of the contract duration in the base case scenario of solar PPAs with 5 kW PV system size installed for both FiT benchmarks.

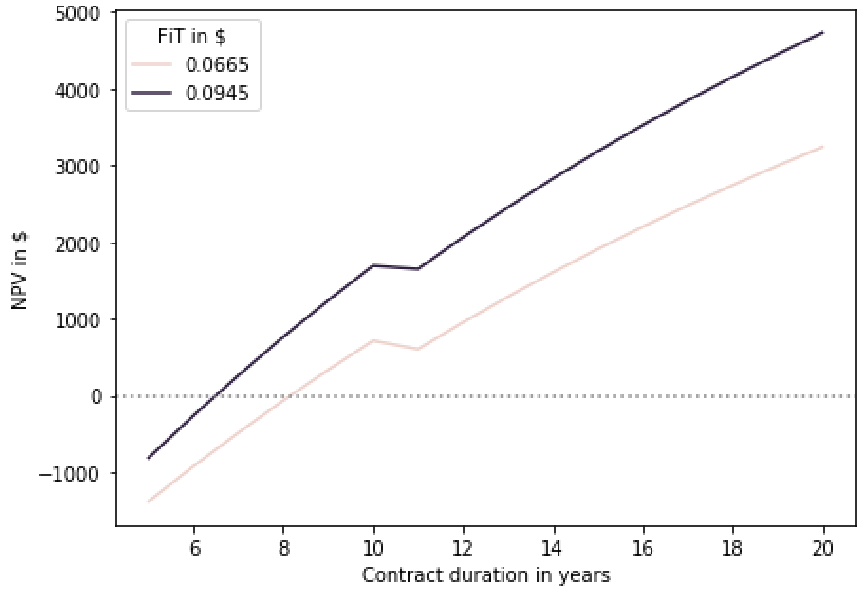

Figure 29: Net present value (NPV) by Feed-in-Tariff (FiT) under a solar PPA with a 5 kW PV system installed for different lengths of contract duration with initial PPA tariff of $p_0^{PPA} = \$0.24$

In general, the NPV increases with increasing contract duration. Only the NPV with a contract duration of eleven years is lower than the NPV with a contract duration of ten years, reflecting the replacement costs of the solar inverter after ten years. For a FiT of $p^{feedin} = \$0.0665$, a third-party would not agree to invest in solar PPAs with a duration of fewer than nine years. For example, for a contract duration of five years, the NPV amounts to -$1382.87. For a contract duration that lasts nine years or longer, the revenue resulting from the solar PPA exceeds the initial investment costs and annual O&M costs of the PV system for $p^{feedin} = \$0.0665$, and the third-party expects a net profit of $1905.41 for 15 years of PPA duration. Clearly, the NPV at the higher FiT $p^{feedin} = \$0.0945$ exceeds the NPV at the lower FiT $p^{feedin} = \$0.0665$ for all contract durations. For a FiT of $p^{feedin} = \$0.0945$, solar PPAs are financially viable with a duration of equal to or higher than seven years. Expecting a NPV of -$815.75, third-parties would not conclude a solar PPA with a contract duration of five years.

We refer to *Appendix F* for more information about the NPV as a function of the contract duration for different initial PPA tariffs. Generally, the higher the initial PPA tariff and the higher the FiT, the more economically beneficial is the investment in solar PPAs given a specific contract duration.

Solar-and-storage PPAs

Figure 30 depicts the NPV as a function of contract duration in the base case scenario of solar-and-storage PPAs with a 5 kW PV system and a 5 kWh BESS installed, respectively.

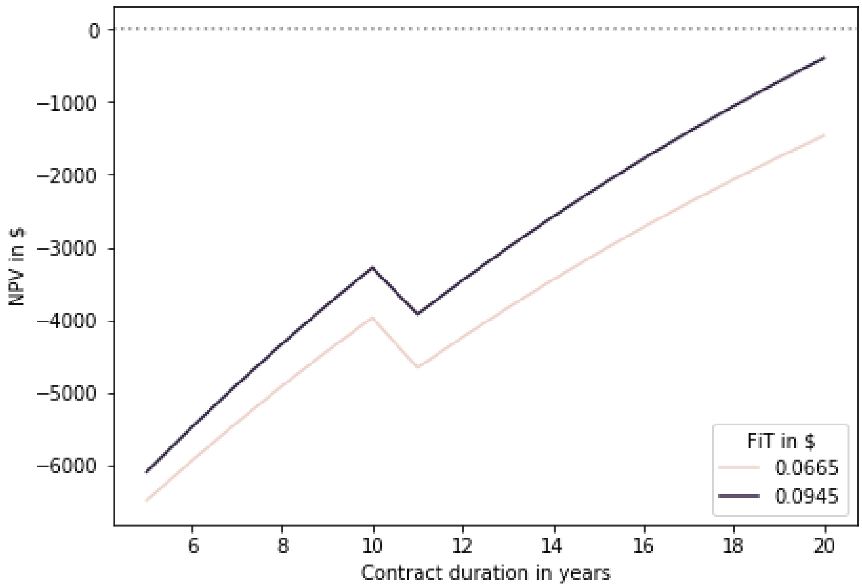

Figure 30: Net present value (NPV) by Feed-in-Tariff (FiT) under a solar-and-storage PPA with a 5 kW PV system and a 5 kWh BESS installed for different lengths of contract duration with initial PPA tariff of $p_0^{PPA} = \$0.24$

Again, the NPV increases with increasing contract duration besides the single decrease at eleven years of contract duration, reflecting the replacement costs of the hybrid inverter of the PV+BESS. The higher FiT results in a higher NPV for all contract durations. The third-party receives a net profit of -$6491.14 at $p^{feedin} = \$0.0665$ and -$6095.75 at $p^{feedin} = \$0.0945$ for a duration of five years, respectively. Both NPVs increases to -$3970.27 at $p^{feedin} = \$0.0665$ and -$3281.70 at $p^{feedin} = \$0.0945$ for a contract duration of ten years. The additional costs for the hybrid inverter replacement after ten years leads to a decrease at eleven years of PPA duration for both FiTs. Nevertheless, investing in solar-and-storage PPAs remains economically unbeneficial from the third-party perspective for each contract duration considered at both FiTs. Overall, the best option for the third-party is to agree to a solar-and-storage PPA with a contract duration of 20 years under current assumptions.

Again, we refer to *Appendix F* for more information about the NPV as a function of the contract duration for different initial PPA tariffs. A higher initial PPA tariff and a higher FiT increases the NPV of solar-and-storage PPAs given a specific contract duration. For example, an initial PPA tariff of $p_0^{PPA} = \$0.28$ and a FiT of $p^{feedin} = \$0.0945$ leads to a positive NPV when the contract duration exceeds 17 years, making the investment in solar-and-storage PPAs economically for the third-party.

5. Conclusions

This study investigates if and under which conditions third-party financed residential solar and solar-and-storage PPAs can be economically beneficial with representative households as customers in Australia. First, we develop a framework to design residential solar PPAs with BESSs and explain the impact of the design parameters contract duration, PPA tariff structure and PV+BESS sizing on the financial viability of solar-and-storage PPAs. Second, we implement a two-step techno-economic model to determine the financial viability of solar and solar-and-storage PPAs from a third-party and customer perspective. Hereby, we assume calibrate parameters based on current PV system and BESS investment costs and electricity tariffs in Australia. Representative electricity consumption and generation profiles are generated using a stationary bootstrap approach, based on information about real-world electricity consumption and generation data. In addition, this study includes a model for residential BESSs, developed based on previous research and real-world battery storage characteristics, such as degradation and round trip efficiency. The BESS operates solely to increase the self-consumption and self-sufficiency. All calculations are based on half-hourly resolution data, enabling a realistic and accurate determination of the electricity usage and financial cashflows in the model setup. However, further work could extend the resolution to continuous real-time data to enhance the performance measurement of the BESS.

We find that financing a PV system only located onsite the customer under solar PPAs is an economically beneficial option for both the third-party and the customer in the current Australian market environment. For the third-party, the implementation of a 5 kW PV system results in a NPV of $2696.58 assuming the FiT benchmark for 2020/21 of $0.0665 in a base scenario. In general, we find that a higher PPA tariff increases the net profit for the third party. The expected NPV mainly depends on the PV system size installed and the FiT applied. A higher FiT indicates a higher NPV for the same PV system size installed, financially supporting the installation of a larger PV system. In contrast, we find that a lower FiT can mitigate the net profit of the third-party for a higher PV system size installed, since the revenue generated from feeding electricity into the grid under FiT cannot counterbalance the additional PV investment costs for a larger PV system. This effect can be linked to the time-mismatch of solar-generated electricity and residential consumption patterns. From a PV system of 2 kW or larger, the main share of solar-generated electricity is fed into the grid, which weights the proportion of the revenue resulting from feeding in higher than the one resulting from the customer’s amount of electricity self-consumed.

We find that the implementation of a BESS in addition to the PV system increases the amount of electricity self-consumed by the customer. Depending on PV system size, a 5 kWh BESS provides about 7% to 26% more solar-generated electricity for the electricity consumption of the customer over 20 years.

Although the BESS installation increases self-consumption and self-sufficiency, we find that financing a PV+BESS under a solar-and-storage PPA is typically not financially viable for the third-party. The initial investment costs of the BESSs are too high to compensate for the additional revenue generated from selling a higher amount of electricity to the customers. However, solar-and-storage PPAs may become economically feasible with a lower BESS size installed and lower upfront investment costs. Like in solar PPAs, a higher PPA tariff results in a higher NPV, but even the highest initial PPA tariff of $0.28 considered leads to a negative NPV for a 5 kWh BESS installation. However, rebates on the upfront investment costs of the BESS can make entering into a solar-and-storage PPA an economically beneficial option for the third-party. Our results indicate that with a rebate of at least $1103.82, the investment in a solar-and-storage PPA with a 5 kW PV system and a 5 kWh BESS installed can be financially viable at an initial PPA tariff of $0.28.

One general finding is that BESSs support the installation of a larger PV system size. The revenue resulting from selling the electricity stored to the customer instead of feeding into the grid exceeds the investment costs of larger PV systems. Hence, we conclude that BESS installation can increase the share of residential PV capacity, once the BESS costs decline. Similar to solar PPAs, higher FiTs result in higher net profits for the third-party.

For common Australian customers, we find that both solar and solar-and-storage PPAs are financially viable options to install either a PV system or a PV+BESS on their property, whereas the incentive for customers to invest in solar PPAs is rather low. Under solar PPAs with our base assumptions, flat-rate customers can save $1678.87 and TOU customer $5591.36 on their net electricity bills within a contract duration of 20 years for a 5 kW PV system installed. The individual risk attitude, personal preferences and motivations to install PV system may further impact the decision of a household to enter into a solar PPA. As expected, customers can save more money on their electricity bill when installing a combined PV+BESS instead of PV only. The BESS increases the self-sufficiency without any additional costs to the customer. A commonly sized BESS with 5 kWh storage capacity increases the self-sufficiency and consequently the electricity bill savings of the customer. Flat-rate customers can save $2992.16 and TOU $8791.36 on their electricity bills, which makes solar-and-storage PPAs a beneficial solution for customers to install a PV+BESS on their property. Under both solar and solar-and-storage PPAs, the results indicate that TOU customers generally save more on their electricity bills than flat-rate customers, as they profit from a higher spread of PPA tariff and retail tariff in peak times. Also, the BESS supplies most of the electricity in the late afternoon and evening hours, leveraging the benefits resulting from the tariff spread for the customer. Furthermore, both a larger BESS and a larger PV system increase the self-sufficiency and, thus, the electricity bill savings for solar and solar-and-storage PPAs. Additionally, customers save more on their electricity bill with a lower initial PPA tariff.

In summary, the findings of solar and solar-and-storage PPAs from a financial point of view indicate that third-parties prefer the financing of a PV system only over a combined PV+BESS, and customers financially benefit more from a combined PV+BESS than from a PV system only. Also, a higher initial PPA tariff under solar-and-storage PPAs than under solar PPAs only typically does not make the investment in solar-and-storage PPAs financially advantageous, in comparison to solar PPAs for the third-party. However, policy measures, such as battery rebates, FiTs and PPAs offered by the Government, can enhance the financial viability for the third-party. Our results indicate that current battery rebate programs already lead to a positive net profit under solar-and-storage PPAs. Furthermore, we find residential PPAs financed by the Government could be a financially viable option to stimulate the installation of residential PV+BESS.

This work provides a comprehensive understanding of the financial viability of residential solar and solar-and-storage PPAs in Australia, but is restricted to model assumptions and includes further limitation that are summarized in the following.

First, it should be noted that we evaluated the installation of a residential BESS in addition to a PV system under solar-and-storage PPAs by modelling one specific BESS. The technical characteristics of the BESS, such as round trip efficiency and maximum (dis-)charging rate, directly influence the performance of the BESS and, thus, affect the electricity usage under solar-and-storage PPAs. Future work may extend the current analysis by a variation of BESS technical characteristics to make a more comprehensive statement about the economic benefits of solar-and-storage PPAs from the third-party and the customer perspective. In addition, the evaluation of the economic benefits of residential BESSs in this work is limited to the assumption that the BESS only operates to meet the demand of the customer. However, battery storage is a multi-purpose technology that can stabilize the grid, enables peak demand shaving and can contribute to price stability on the wholesales market (Lund et al., 2015; Malhotra et al., 2016). How residential on-grid BESSs can be applied in the context of solar-and-storage PPAs to enable load shifting, demand-side-management, and peak demand reduction through interactions with the grid is subject to further work. In this context, future research may also consider time-variant FiTs. Some states in Australia have already introduced time-variant FiTs, encouraging residents to feed in solar-generated electricity in off-peak times, especially in the evening hours (IPART, 2021a; Solar Choice, 2018). For example, in NSW, currently only 2% of the total electricity feed in takes place after 5 pm (IPART, 2021a). This study does not consider time-variant FiTs, as most of the electricity is fed in to times where the time-variant FiT equals the traditional FiT due to the BESS cycling. Nevertheless, the impact of time-dependent FiTs on the financial viability of on-grid BESSs under solar-and-storage PPAs is more complex and remains future work.

Furthermore, this work evaluates residential PPAs for one customer segment solely with average annual electricity consumption of about 4680.33 kWh. However, future work could analyse the sensitivity of solar and solar-and-storage PPAs regarding the level of residential electricity consumption. We expect that higher residential electricity consumption will increase the economic benefit of solar and solar-and-storage PPAs, as the residents draw a higher share of the solar-generated electricity during the whole day, which would be consistent with Best et al. (2019). Under solar-and-storage PPAs, higher residential electricity consumption may increase the utilization of BESS. Households retrieve more electricity stored in evening hours, enabling deeper cycles of the BESS, increasing the share of electricity stored, and mitigating the electricity fed in on a long-term perspective.

Another opportunity in terms of increasing the financial viability of residential solar and solar-and-storage PPAs is to include electric vehicles in the financial analysis of PPAs. With improved battery technology, electric vehicles have become usable low-emission alternatives to fuel-powered cars for households and have already gained high popularity in many regions like Europe and the USA (Hall and Lutsey, 2017). One major potential of electric vehicles is their ability to provide vehicle-to-grid flexibility services that enable grid-connected local electricity management by utilizing the battery inside the electric vehicle for load-shifting and peak demand reduction (International Renewable Energy Agency, 2017). Also, the adoption of electric vehicles to residential PV systems increases the household’s self-consumption (Munkhammar et al., 2013). However, in Australia, the market penetration of electric vehicles is still low, as households, among others, refuse to pay high purchase prices and O&M costs (Gong et al., 2020). In addition, electric vehicles increase the electricity consumption and consequently the electricity bills of households in general, making the financial viability of electric vehicles for households dependent on future electricity prices. In this context, residential PPAs can be a viable alternative for residents to overcome the financial risks of electric vehicles and remains an interesting topic for future research.

References

Ausgrid, 2021. Solar home electricity data. https://www.ausgrid.com.au/Industry/Our-Research/Data-to-share/Solar-home-electricity-data (accessed 24 April 2021).

Australian Energy Market Operator, 2020. 2020 Electricity Statement of Opportunities: A report for the National Electricity Market. https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2020/2020-electricity-statement-of-opportunities.pdf?la=en (accessed 13 May 2021).

Australian Energy Regulator, 2020. State of the Energy Market 2020. https://www.aer.gov.au/system/files/State%20of%20the%20energy%20market%202020%20-%20Full%20report%20A4.pdf.

Australian Energy Regulator, 2021. Annual electricity consumption - NEM. https://www.aer.gov.au/wholesale-markets/wholesale-statistics/annual-electricity-consumption-nem (accessed 13 May 2021).

Australian Government Department of the Environment and Energy, 2019. National greenhouse accounts factors: Australian National Greenhouse Accounts. https://www.industry.gov.au/sites/default/files/2020-07/national-greenhouse-accounts-factors-august-2019.pdf (accessed 4 May 2021).

Australian PV Institute, 2021. Mapping Australian Photovoltaic installations. https://pv-map.apvi.org.au/historical#4/-26.67/134.12 (accessed 28 April 2021).

Babacan, O., Ratnam, E.L., Disfani, V.R., Kleissl, J., 2017. Distributed energy storage system scheduling considering tariff structure, energy arbitrage and solar PV penetration. Applied Energy 205, 1384–1393. https://doi.org/10.1016/j.apenergy.2017.08.025.

Baek, Y., Collingsworth, J., Clemmer, S., Gignac, J., Jacobs, M., Garcia, P., Sattler, S., 2020. The economic feasibility of solar and storage system in Illinois. The Electricity Journal 33, 106689. https://doi.org/10.1016/j.tej.2019.106689.

Bahadori, A., Nwaoha, C., 2013. A review on solar energy utilisation in Australia. Renewable and Sustainable Energy Reviews 18, 1–5. https://doi.org/10.1016/j.rser.2012.10.003.

Balcombe, P., Rigby, D., Azapagic, A., 2014. Investigating the importance of motivations and barriers related to microgeneration uptake in the UK. Applied Energy 130, 403–418. https://doi.org/10.1016/j.apenergy.2014.05.047.

Baumann, M., Peters, J.F., Weil, M., Grunwald, A., 2017. CO 2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications. Energy Technol. 5, 1071–1083. https://doi.org/10.1002/ente.201600622.

Best, R., Li, H., Trück, S., Truong, C., 2021. Actual uptake of home batteries: The key roles of capital and policy. Energy Policy 151, 112186. https://doi.org/10.1016/j.enpol.2021.112186.

Best, R., Trück, S., 2020. Capital and policy impacts on Australian small-scale solar installations. Energy Policy 136, 111082. https://doi.org/10.1016/j.enpol.2019.111082.

Best, R., Trück, S., Truong, C., Yu, L., 2019. The Financial Analysis of Residential Solar Power Purchase Agreements. Working Paper, Centre for Risk Analytics.

BloombergNEF, 2021. Corporate Clean Energy Buying Leapt 44% in 2019, Sets New Record. https://about.bnef.com/blog/corporate-clean-energy-buying-leapt-44-in-2019-sets-new-record/ (accessed 24 April 2021).

Bolinger, M., Holt, E., 2015. A Survey of State and Local PV Program Response to Financial Innovation and Disparate Federal Tax Treatment in the Residential PV Sector. Lawrence Berkeley National Laboratory. https://escholarship.org/uc/item/8q81r6c1.

Brakels, R., 2016. Solar Panel Rebate To Be Phased Out From 1st of January 2017. https://www.solarquotes.com.au/blog/solar-panel-rebate-phased-1st-january-2017/ (accessed 7 May 2021).

Braun, M., Büdenbender, K., Magnor, D., Jossen, A., 2009. Photovoltaic self-consumption in Germany - Using lithium-ion storage to increase self-consumed photovoltaic energy. 24th European Photovoltaic Solar Energy Conference (PVSEC).
Bureau of Meteorology, 2013. Special Climate Statement 43 – extreme heat in January 2013. http://www.bom.gov.au/climate/current/statements/scs43e.pdf (accessed 6 May 2021).
Bureau of Meteorology New South Wales Climate Services Centre, 2011. An exceptional summer heatwave in greater Sydney and the Hunter Valley.: Special Climate Statement 27. http://www.bom.gov.au/climate/current/statements/scs27.pdf (accessed 6 May 2021).
Büsgen, U., Dürrschmidt, W., 2009. The expansion of electricity generation from renewable energies in Germany. Energy Policy 37, 2536–2545. https://doi.org/10.1016/j.enpol.2008.10.048.
Business Renewables Centre-Australia, 2019. Corporate Renewable Power Purchase Agreements: State of the Market 2019. https://arena.gov.au/assets/2018/10/corporate-renewable-power-purchase-agreements-in-australia-state-of-the-market-2019.pdf.
Carnegie, R., Gotham, D., Nderitu, D., Preckel, P.V., 2013. Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies. https://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf.
Chapman, A.J., McLellan, B., Tezuka, T., 2016. Residential solar PV policy: An analysis of impacts, successes and failures in the Australian case. Renewable Energy 86, 1265–1279. https://doi.org/10.1016/j.renene.2015.09.061.
Clean Energy Council, 2020a. Clean Energy Australia Report 2020. https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2020.pdf.
Clean Energy Council, 2020b. Energy Storage. https://www.cleanenergycouncil.org.au/resources/technologies/energy-storage (accessed 28 April 2021).
Clean Energy Regulator, 2021a. Renewable Energy Target. http://www.cleanenergyregulator.gov.au/RET/Pages/default.aspx (accessed 24 April 2021).
Clean Energy Regulator, 2021b. Small-scale technology certificates. http://www.cleanenergyregulator.gov.au/RET/Scheme-participants-and-industry/Agents-and-installers/Small-scale-technology-certificates (accessed 24 April 2021).
Cleveland, R.B., Cleveland, W.S., McRae, Jean E adn Terpenning, Irma, 1990. STL: A seasonal-trend decomposition procedure based on loess. Journal of Official Statistics 6, 3–73.
Cleveland, W.S., 1979. Robust Locally Weighted Regression and Smoothing Scatterplots. Journal of the American Statistical Association 74, 829. https://doi.org/10.2307/2286407.
Colmenar-Santos, A., Campíñez-Romero, S., Pérez-Molina, C., Castro-Gil, M., 2012. Profitability analysis of grid-connected photovoltaic facilities for household electricity self-sufficiency. Energy Policy 51, 749–764. https://doi.org/10.1016/j.enpol.2012.09.023.
Commonwealth of Australia, 2015. Australia's 2030 Emission Reduction Target. https://www.pmc.gov.au/.
Cory, K., Canavan, B., Koenig, R., 2009. Power Purchase Agreement Checklist for State and Local Governments. https://digital.library.unt.edu/ark:/67531/metadc929549/ (accessed 24 April 2021).
Cory, K., Coughlin, J., Coggeshall, C., 2008. Solar Photovoltaic Financing: Deployment on Public Property by State and Local Governments. National Renewable Energy Laboratory.
Coughlin, J., Cory, K., 2009. Solar Photovoltaic Financing: Residential Sector Deployment.
2018. CUB secures bright future. https://cub.com.au/cub-secures-bright-future/. (accessed 2 April 2021).
Davidson, C., Steinberg, D., Margolis, R., 2015. Exploring the market for third-party-owned residential photovoltaic systems: insights from lease and power-purchase agreement contract structures and costs in California. Environ. Res. Lett. 10, 24006. https://doi.org/10.1088/1748-9326/10/2/024006.

Department of Environment, Land, Water and Planning, 2021. Solar Homes Program. https://www.solar.vic.gov.au/solar-homes-program (accessed 4 May 2021).
Department of Industry, Science, Energy and Resources, 2021. National Electricity Market. https://www.energy.gov.au/government-priorities/energy-markets/national-electricity-market-nem (accessed 13 May 2021).
Diamond Energy, 2019. Residential Customer Energy Price Fact Sheet – NSW Energy Price Fact Sheet – NSW: Retail Supply Offer – Ausgrid – Standing Offer.
Drury, E., Miller, M., Macal, C.M., Graziano, D.J., Heimiller, D., Ozik, J., Perry IV, T.D., 2012. The transformation of southern California's residential photovoltaics market through third-party ownership. Energy Policy 42, 681–690. https://doi.org/10.1016/j.enpol.2011.12.047.
Ellingsen, L.A.-W., Hung, C.R., Strømman, A.H., 2017. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. Transportation Research Part D: Transport and Environment 55, 82–90. https://doi.org/10.1016/j.trd.2017.06.028.
Elphick, S., Drury, G., Fixter, B., 2020. The Impact of Small Scale Solar PV on Power Quality: An Empirical Study, in: 2020 19th International Conference on Harmonics and Quality of Power (ICHQP). 2020 19th International Conference on Harmonics and Quality of Power (ICHQP), Dubai, United Arab Emirates. 2020. IEEE, pp. 1–6.
European Photovoltaic Industry Association, 2011. Solar Photovoltaics competing in the energy sector: On the road to competitiveness.
Figgener, J., Stenzel, P., Kairies, K.-P., Linßen, J., Haberschusz, D., Wessels, O., Angenendt, G., Robinius, M., Stolten, D., Sauer, D.U., 2020. The development of stationary battery storage systems in Germany – A market review. Journal of Energy Storage 29, 101153. https://doi.org/10.1016/j.est.2019.101153.
Foehringer, E., 2019. Hawaiian Electric Announces ‘Mind-Blowing’ Solar-Plus-Storage Contracts. https://www.greentechmedia.com/articles/read/hawaiian-electric-industries-announces-mind-blowing-solar-plus-storage-cont.
García-Alvarez, M.T., Mariz-Pérez, R.M., 2012. Analysis of the Success of Feed-in Tariff for Renewable Energy Promotion Mechanism in the EU: Lessons from Germany and Spain. Procedia - Social and Behavioral Sciences 65, 52–57. https://doi.org/10.1016/j.sbspro.2012.11.090.
Geoscience Australia, 2021. Solar Energy. http://www.ga.gov.au/scientific-topics/energy/resources/other-renewable-energy-resources/solar-energy (accessed 24 April 2021).
Gong, S., Ardeshiri, A., Hossein Rashidi, T., 2020. Impact of government incentives on the market penetration of electric vehicles in Australia. Transportation Research Part D: Transport and Environment 83, 102353. https://doi.org/10.1016/j.trd.2020.102353.
Government of South Australia, 2021. South Australia's Home Battery Scheme: Delivering more affordable, reliable energy for all South Australians. https://homebatteryscheme.sa.gov.au/about-the-scheme (accessed 4 May 2021).
Haberschusz, D., Kairies, K.-P., Wessels, O., Magnor, D., Sauer, D.U., 2017. Are PV Battery Systems Causing Ramping Problems in the German Power Grid? Energy Procedia 135, 424–433. https://doi.org/10.1016/j.egypro.2017.09.512.
Hall, D., Lutsey, N., 2017. Emerging best practices for electric vehicle charging infrastructure. The International Council on Clean Transportation, Washington, DC. https://theicct.org/sites/default/files/publications/EV-charging-best-practices_ICCT-white-paper_04102017_vF.pdf.
Hamwi, M., Lizarralde, I., 2017. A Review of Business Models towards Service-Oriented Electricity Systems. Procedia CIRP 64, 109–114. https://doi.org/10.1016/j.procir.2017.03.032.
Hayat, M.A., Shahnia, F., Shafiullah, G.M., 2018. Economic Viability of Roof Leasing for Rooftop Photovoltaic Systems from a Leasing Company’s Perspective, in: 2018 IEEE 7th World Conference

on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC). 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI. 2018. IEEE, pp. 2399–2404.
Hayat, M.A., Shahnia, F., Shafiullah, G.M., 2019. Technical Analysis of the Charge/Discharge Rate and the Capacity of Batteries in Meeting the Residential Peak Demand within a Community Solar, in: 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia). 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Chengdu, China. 2019. IEEE, pp. 2832–2836.
Hesse, H., Martins, R., Musilek, P., Naumann, M., Truong, C., Jossen, A., 2017. Economic Optimization of Component Sizing for Residential Battery Storage Systems. Energies 10, 835. https://doi.org/10.3390/en10070835.
Hobbs, A., Benamin, E., Varadarajan, U., Pierpont, B., 2013. Improving-Solar-Policy-Lessons-from-the-solar-leasing-boom-in-California. Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/improving-solar-policy-lessons-from-the-solar-leasing-boom-in-california/.
Hong, T., Yoo, H., Kim, J., Koo, C., Jeong, K., Lee, M., Ji, C., Jeong, J., 2018. A model for determining the optimal lease payment in the solar lease business for residences and third-party companies – With focus on the region and on multi-family housing complexes. Renewable and Sustainable Energy Reviews 82, 824–836. https://doi.org/10.1016/j.rser.2017.09.068.
Hoppmann, J., Volland, J., Schmidt, T.S., Hoffmann, V.H., 2014. The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model. Renewable and Sustainable Energy Reviews 39, 1101–1118. https://doi.org/10.1016/j.rser.2014.07.068.
Horváth, D., Szabó, R.Z., 2018. Evolution of photovoltaic business models: Overcoming the main barriers of distributed energy deployment. Renewable and Sustainable Energy Reviews 90, 623–635. https://doi.org/10.1016/j.rser.2018.03.101.
Howland, E., 2020. Starbucks enters into first-ever ‘virtual’ storage PPA. https://www.publicpower.org/periodical/article/starbucks-enters-first-ever-virtual-storage-ppa (accessed 24 April 2021).
Hsu, D., O’Donoughue, P., Fthenakis, V., Heath, G., Kim, H.C., Sawyer, P., Choi, J.-K., Turney, D., 2012. Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation. Journal of Industrial Ecology 16, S122-S135. https://doi.org/10.1111/j.1530-9290.2011.00439.x.
Huijben, J., Verbong, G., 2013. Breakthrough without subsidies? PV business model experiments in the Netherlands. Energy Policy 56, 362–370. https://doi.org/10.1016/j.enpol.2012.12.073.
Hyndman, R.J., 2011. Moving Averages, in: Lovric, M. (Ed.), International Encyclopedia of Statistical Science. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 866–869.
International Renewable Energy Agency, 2017. Electricity storage and renewables: costs and markets to 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf (accessed 24 April 2021).
IPART, 2019. Solar Feed-in Tariff Benchmark 2019-20. https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-energy-services-publications-solar-feed-in-tariffs-201920/final-report-solar-feed-in-tariff-benchmark-2019-20.pdf (accessed 4 May 2021).
IPART, 2020. Solar Feed-in Tariff Benchmark: Final Report. https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-energy-services-publications-solar-feed-in-tariffs-202021/final-report-solar-feed-in-tariffs-202021-april-2020.pdf (accessed 4 May 2021).

IPART, 2021a. Review of solar feed-in tariff benchmarks: Draft Report. https://www.ipart.nsw.gov.au/files/sharedassets/website/shared-files/pricing-reviews-energy-services-publications-solar-feed-in-tariffs-202122/draft-report-review-of-solar-feed-in-tariff-benchmarks-april-2021.pdf (accessed 13 May 2021).
IPART, 2021b. Solar feed-in tariff benchmarks 2021-22 to 2023-24. https://www.ipart.nsw.gov.au/Home/Industries/Energy/Reviews/Electricity/Solar-feed-in-tariff-benchmarks-2021-22-to-2023-24?qDh=0 (accessed 13 May 2021).
Jeff Sykes, 2020. Solar Power Purchase Agreements (PPAs). https://www.solarchoice.net.au/blog/solar-power-purchase-agreements-ppas/ (accessed 4 May 2021).
Jeff Sykes, 2021. The ACT's solar battery storage incentive program. https://www.solarchoice.net.au/blog/act-home-solar-battery-storage-incentive-program (accessed 4 April 2021).
John Parnell, 2019. Bavarian solar-plus-storage subsidy scheme launches today. https://www.energy-storage.news/news/bavarian-solar-plus-storage-subsidy-launches-today (accessed 4 May 2021).
Jordan, D.C., Kurtz, S.R., 2013. Photovoltaic Degradation Rates-an Analytical Review. Prog. Photovolt: Res. Appl. 21, 12–29. https://doi.org/10.1002/pip.1182.
Kollins, K., Speer, B., Cory, K., 2010. Solar PV Project Financing: Regulatory and Legislative Challenges for Third-Party PPA System Owners, Golden, Colorado. https://www.nrel.gov/docs/fy10osti/46723.pdf.
Kulatilaka, N., Santiago, L., Vakili, P., 2014. Reallocating risks and returns to scale up adoption of distributed electricity resources. Energy Policy 69, 566–574. https://doi.org/10.1016/j.enpol.2014.02.005.
Kumar Sahu, B., 2015. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. Renewable and Sustainable Energy Reviews 43, 621–634. https://doi.org/10.1016/j.rser.2014.11.058.
Lahiri, S.N., 1999. Theoretical Comparisons of Block Bootstrap Methods. The Annals of Statistics 27, 386–404.
Lauber, V., Mez, L., 2004. Three Decades of Renewable Electricity Policies in Germany. Energy & Environment 15, 599–623. https://doi.org/10.1260/0958305042259792.
Leadbetter, J., Swan, L., 2012. Battery storage system for residential electricity peak demand shaving. Energy and Buildings 55, 685–692. https://doi.org/10.1016/j.enbuild.2012.09.035.
Li, Y., 2018. Incentive pass-through in the California Solar Initiative – An analysis based on third-party contracts. Energy Policy 121, 534–541. https://doi.org/10.1016/j.enpol.2018.07.015.
Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews 45, 785–807. https://doi.org/10.1016/j.rser.2015.01.057.
Luthander, R., Widén, J., Nilsson, D., Palm, J., 2015. Photovoltaic self-consumption in buildings: A review. Applied Energy, 142, 80-94. https://doi.org/10.1016/j.apenergy.2014.12.028.
Macintosh, A., Wilkinson, D., 2011. Searching for public benefits in solar subsidies: A case study on the Australian government's residential photovoltaic rebate program. Energy Policy 39, 3199–3209. https://doi.org/10.1016/j.enpol.2011.03.007.
Maisch, M., 2019. Australia could install 179 GW of rooftop solar. https://www.pv-magazine-australia.com/2019/06/13/australia-could-install-179-gw-of-rooftop-solar/ (accessed 8 June 2021).
Malhotra, A., Battke, B., Beuse, M., Stephan, A., Schmidt, T., 2016. Use cases for stationary battery technologies: A review of the literature and existing projects. Renewable and Sustainable Energy Reviews, 56, 705-721. https://doi.org/10.1016/j.rser.2015.11.085.
Martin II, J., 2015. Hybrid inverters vs battery inverters for home solar energy storage. https://www.solarchoice.net.au/blog/hybrid-inverters-battery-inverters-home-energy-storage/ (accessed 15 May 2021).

Masoumzadeh, A., Nekouei, E., Alpcan, T., Chattopadhyay, D., 2018. Impact of Optimal Storage Allocation on Price Volatility in Energy-Only Electricity Markets. IEEE Trans. Power Syst. 33, 1903–1914. https://doi.org/10.1109/TPWRS.2017.2727075.
Mayr, F., 2020. Battery storage at US$20/MWh? Breaking down low-cost solar-plus-storage PPAs in the USA. https://www.energy-storage.news/blogs/battery-storage-at-us20-mwh-breaking-down-low-cost-solar-plus-storage-ppas (accessed 7 May 2021).
Mendicino, L., Menniti, D., Pinnarelli, A., Sorrentino, N., 2019. Corporate power purchase agreement: Formulation of the related levelized cost of energy and its application to a real life case study. Applied Energy 253, 113577. https://doi.org/10.1016/j.apenergy.2019.113577.
Microsoft, 2017. Microsoft announces largest wind energy deal in the Netherlands. https://news.microsoft.com/europe/2017/11/02/microsoft-announces-largest-wind-energy-deal-in-the-netherlands/ (accessed 2 April 2021).
Miller, L., Carriveau, R., 2018. A review of energy storage financing—Learning from and partnering with the renewable energy industry. Journal of Energy Storage 19, 311–319. https://doi.org/10.1016/j.est.2018.08.007.
Mullendore, S., 2014. Walmart + SolarCity = Solar + Storage. Clean Energy Group. https://www.cleanegroup.org/walmart-solarcity-solar-storage/ (accessed 8 June 2021).
Mulleriyawage, U., Shen, W.X., 2020. Optimally sizing of battery energy storage capacity by operational optimization of residential PV-Battery systems: An Australian household case study. Renewable Energy 160, 852–864. https://doi.org/10.1016/j.renene.2020.07.022.
Munkhammar, J., Grahn, P., Widén, J., 2013. Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging. Solar Energy 97, 208–216. https://doi.org/10.1016/j.solener.2013.08.015.
Natur Solar, 2020. Solar Battery Rebates Victoria. https://naturalsolar.com.au/vic-solar-battery-rebate/ (accessed 24 April 2021).
Nyholm, E., Goop, J., Odenberger, M., Johnsson, F., 2016. Solar photovoltaic-battery systems in Swedish households – Self-consumption and self-sufficiency. Applied Energy 183, 148–159. https://doi.org/10.1016/j.apenergy.2016.08.172.
Nykvist, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Clim Change 5, 329–332. https://doi.org/10.1038/nclimate2564.
Olaszi, B.D., Ladanyi, J., 2017. Comparison of different discharge strategies of grid-connected residential PV systems with energy storage in perspective of optimal battery energy storage system sizing. Renewable and Sustainable Energy Reviews 75, 710–718. https://doi.org/10.1016/j.rser.2016.11.046.
Oliva H., S., Passey, R., Abdullah, M.A., 2019. A semi-empirical financial assessment of combining residential photovoltaics, energy efficiency and battery storage systems. Renewable and Sustainable Energy Reviews 105, 206–214. https://doi.org/10.1016/j.rser.2019.01.042.
Oliveira e Silva, G. de, Hendrick, P., 2016. Lead–acid batteries coupled with photovoltaics for increased electricity self-sufficiency in households. Applied Energy 178, 856–867. https://doi.org/10.1016/j.apenergy.2016.06.003.
Palm, J., 2018. Household installation of solar panels – Motives and barriers in a 10-year perspective. Energy Policy 113, 1–8. https://doi.org/10.1016/j.enpol.2017.10.047.
Parra, D., Patel, M.K., 2016. Effect of tariffs on the performance and economic benefits of PV-coupled battery systems. Applied Energy 164, 175–187. https://doi.org/10.1016/j.apenergy.2015.11.037.
Pichai, S., 2019. Our biggest renewable energy purchase ever. https://blog.google/outreach-initiatives/sustainability/our-biggest-renewable-energy-purchase-ever/ (accessed 2 April 2021).
Politis, D.N., Romano, J.P., 1994. The Stationary Bootstrap. Journal of the American Statistical Association 89, 1303. https://doi.org/10.2307/2290993.
Politis, D.N., White, H., 2004. Automatic Block-Length Selection for the Dependent Bootstrap. Econometric Reviews 23, 53–70. https://doi.org/10.1081/ETC-120028836.

Poruschi, L., Ambrey, C.L., Smart, J.C., 2018. Revisiting feed-in tariffs in Australia: A review. Renewable and Sustainable Energy Reviews 82, 260–270. https://doi.org/10.1016/j.rser.2017.09.027.
Rai, A., Nunn, O., 2020. On the impact of increasing penetration of variable renewables on electricity spot price extremes in Australia. Economic analysis and policy 67, 67–86. https://doi.org/10.1016/j.eap.2020.06.001.
Ren, Z., Grozev, G., Higgins, A., 2016. Modelling impact of PV battery systems on energy consumption and bill savings of Australian houses under alternative tariff structures. Renewable Energy 89, 317–330. https://doi.org/10.1016/j.renene.2015.12.021.
REN21, 2020. Renewables 2020: Global Status Report. https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf.
Roberts, M.B., Bruce, A., MacGill, I., 2019a. A comparison of arrangements for increasing self-consumption and maximising the value of distributed photovoltaics on apartment buildings. Solar Energy 193, 372–386. https://doi.org/10.1016/j.solener.2019.09.067.
Roberts, M.B., Bruce, A., MacGill, I., 2019b. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. Applied Energy 245, 78–95. https://doi.org/10.1016/j.apenergy.2019.04.001.
Romare, M., Dahllöf, L., 2017. The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for light-duty vehicles. http://www.hpv.popol.eu/co2report.pdf (accessed 14 May 2021).
Ryan, P., Pavia, M., 2016. Australian Residential Energy End-Use – Trends and projections to 2030. American Council for an Energy-Efficient Economy. https://www.aceee.org/files/proceedings/2016/data/papers/9_286.pdf.
Schopfer, S., Tiefenbeck, V., Staake, T., 2018. Economic assessment of photovoltaic battery systems based on household load profiles. Applied Energy 223, 229–248. https://doi.org/10.1016/j.apenergy.2018.03.185.
Seabold, S., Perktold, J., 2010. statsmodels: Econometric and statistical modeling with python, in: 9th Python in Science Conference.
SEIA, 2020. Solar Investment Tax Credit (ITC). https://www.seia.org/initiatives/solar-investment-tax-credit-itc (accessed 4 May 2021).
Sharma, A., Roberts, M., MacGill, I., 2019. Analyzing Economic Benefits of Installing Rooftop PV on Real Apartments Buildings. Asia Pacific Solar Research Conference.
Solahart, 2021. South Australia Home Battery Scheme. https://solahart.com.au/landing-pages/sa-home-battery-scheme/ (accessed 4 May 2021).
Solangi, K.H., Islam, M.R., Saidur, R., Rahim, N.A., Fayaz, H., 2011. A review on global solar energy policy. Renewable and Sustainable Energy Reviews 15, 2149–2163. https://doi.org/10.1016/j.rser.2011.01.007.
Solar Choice, 2018. Should you get Victoria’s time-varying solar feed-in tariff? (Analysis & calculator). https://www.solarchoice.net.au/blog/should-you-get-victorias-time-varying-solar-feed-in-tariff-analysis-calculator/ (accessed 13 May 2021).
Solar Choice, 2021a. Residential Solar PV Price Index – March 2021. https://www.solarchoice.net.au/blog/residential-solar-pv-price-index-march-2021/ (accessed 4 May 2021).
Solar Choice, 2021b. Solar Feed-in Tariffs – State by State. https://www.solarchoice.net.au/solar-rebates/solar-feed-in-rewards (accessed 24 April 2021).
Solar Energy Industries Association, 2021. Third-Party Solar Financing. https://www.seia.org/initiatives/third-party-solar-financing (accessed 7 May 2021).
SolarQuotes, 2021. Solar Battery Storage Comparison Table. https://www.solarquotes.com.au/battery-storage/comparison-table/ (accessed 5 February 2021).

Sommerfeld, J., Buys, L., Mengersen, K., Vine, D., 2017. Influence of demographic variables on uptake of domestic solar photovoltaic technology. Renewable and Sustainable Energy Reviews 67, 315–323. https://doi.org/10.1016/j.rser.2016.09.009.
Speer, B., 2012. Residential Solar Photovoltaics: Comparison of Financing Benefits, Innovations, and Options. National Renewable Energy Lab.(NREL), Golden, CO (United States).
Strupeit, L., Palm, A., 2016. Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in Japan, Germany and the United States. Journal of Cleaner Production 123, 124–136. https://doi.org/10.1016/j.jclepro.2015.06.120.
Thumann, A., Woodroof, E.A., 2009. Energy Project Financing: Resources and Strategies for Success.
Tisheva, P., 2017. Aussie telecom Telstra signs 70-MW solar PPA with RES. https://renewablesnow.com/news/aussie-telecom-telstra-signs-70-mw-solar-ppa-with-res-570567/ (accessed 2 April 2021).
van der Stelt, S., AlSkaif, T., van Sark, W., 2018. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. Applied Energy 209, 266–276. https://doi.org/10.1016/j.apenergy.2017.10.096.
Wei, W.W.S., 2006. Time series analysis: Univariate and multivariate methods, 2nd ed. Pearson/Addison Wesley, Boston, Mass., 614 pp.
World Government Bonds, 2021. Australia 20 Years Bond - Historical Data. http://www.worldgovernmentbonds.com/bond-historical-data/australia/20-years/ (accessed 22 June 2021).
Wozabal, D., Graf, C., Hirschmann, D., 2016. The effect of intermittent renewables on the electricity price variance. OR Spectrum 38, 687–709. https://doi.org/10.1007/s00291-015-0395-x.
Young, S., Macgill, I., Bruce, A., 2018. Impacts of PV System Configuration, Retail Tariffs and Annual Household Consumption on Payback Times for Residential Battery Energy Storage. Asia Pacific Solar Research Conference.
Zander, K.K., 2020. Unrealised opportunities for residential solar panels in Australia. Energy Policy 142, 111508. https://doi.org/10.1016/j.enpol.2020.111508.
Zhang, S., 2016. Innovative business models and financing mechanisms for distributed solar PV (DSPV) deployment in China. Energy Policy 95, 458–467. https://doi.org/10.1016/j.enpol.2016.01.022.