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Beyond the Diffusion of Residential Solar Photovoltaic Systems at Scale: Allegorising the Battery Energy Storage Adoption Behaviour

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Abstract: Understanding the residential adoption decision of battery energy storage systems (BESSs) is central to the implementation of successful intervention policies. However, when the residential solar photovoltaics (PV) becomes a widely accepted technology across a society, accurately modelling the behaviour shows a higher degree of complexity. In this vein, the uptake pathway of BESS and PV coupled with BESS (PV–BESS) would predictably exhibit similar attitudinal traits to that of PV consumption. This notion implies that the antecedent PV decision can be regarded as the past behaviour of the BESS adopter by creating attitudinal implications. The PV use status also yields a higher degree of heterogeneity through the emergence of four new household groups and the inherent imbalances in the involvement of the interwoven financial, technical, sociodemographic, and psychological predictors. This perspective employs the Reasoned Action Approach (RAA) to allegorise a decision-making model of BESS and PV–BESS adoption behaviour in a mature PV market (Australia). It argues that the particularised background factors will likely shape the individual's attitudes and perceived norms for intention, and showcases affordability and the use of PV as the two control components that dictate the final decision.

Keywords: battery energy storage system; solar photovoltaic; household; adoption behaviour; reasoned action approach; technology diffusion

Citation: Alipour, M.; Stewart, R.A.; Sahin, O. Beyond the Diffusion of Residential Solar Photovoltaic Systems at Scale: Allegorising the Battery Energy Storage Adoption Behaviour. *Energies* **2021**, *14*, 5015. https://doi.org/10.3390/en14165015

Academic Editors: Chi-Ming Lai and Teuvo Suntio

Received: 16 July 2021
Accepted: 11 August 2021
Published: 16 August 2021

1. Introduction

Over the past few decades, residential rooftop solar photovoltaic (PV) technology has symbolised the desire of end users to take a practical initiative to socio-environmental demand. Governments have been offering generous incentive mechanisms to the diffusion rate of residential PV [1]. While PV systems contribute to the sustainability agenda, the disruptive nature of the technology poses substantial challenges to the traditional electricity distribution network [2]. To address the economic and technical impacts on the grid and electricity market, the battery energy storage system (BESS) has emerged as a new player in the electricity supply system [3]. As fast-growing BESS becomes affordable, the future PV coupled with BESS (PV–BESS) epitomises an autonomous energy system in the residential sector [3–5].

However, the success or failure in the deployment policies concerning the uptake of these distributed resources ultimately hinges on households' bounded rational decisions [6]. Households are the main actors in the uptake decision-making process and, as such, decide whether and to what extent any considered BESS deployment policies may succeed. The critical role of homeowners in the uptake no-go decision calls for a deeper understanding of their decision behaviours to develop effective policy measures. Nevertheless, understanding BESS and PV–BESS adoption decisions can be a challenging task because the complexity of the behaviour arises from a set of interwoven financial, technical, sociodemographic, and psychological attributes. Realising the behaviour can become even more complex when BESS adoption is closely in conjunction with the PV adoption decision—that is, the uptake of one innovation (i.e., BESS) financially, technically, or psychologically is strongly linked to another (i.e., PV). In addition, the range of distinct household groups emerging from PV use status interpolates more opaque intricacy into the cognitive landscape.

The incorporation of all these new components to the models that exist in the literature questions their validity in accurately understanding the BESS and PV–BESS adoption behaviour. It can be argued that the role of PV on BESS, new groups of households, and the linkage and predictors between PV and BESS have yet to be discussed in the literature. If the nuances of this new paradigm are not captured, the managerial policies would fail and result in more social inequities. To facilitate understanding and modelling the behaviour for the implementation of successful intervention policies, this study strives to exemplify a Behavioural Decision-Making Model (BDMM) of household BESS and PV–BESS adopters in a mature PV market (Figure 1). The development of the model emphasises that, unlike modelling PV decision, BESS adoption decision incorporates much more complex decision-making landscapes. The model breakdowns key elements that are required in building two closely related renewable technology adoption by a household. To do so, the research first describes the various implications of the PV use decision (Section 2). It then proposes a novel categorisation of households, not just based on the personal characteristics nor based on estimations but on the actual facts (Section 3). The research continues to briefly introduce the Reasoned Action Approach (RAA) as an appropriate model for the topic and background factors particularising the composition of the individual, social, and techno-economic parameters, which characterise the decision components of heterogeneous individuals (Section 4). The aggregation of these components aids the building of a pilot BDMM (Section 5). Worth mentioning too is that the nature of the developed model in this study is primitive and descriptive. The state of Queensland, Australia, is used as a desirable example with a high penetration rate of home PV.

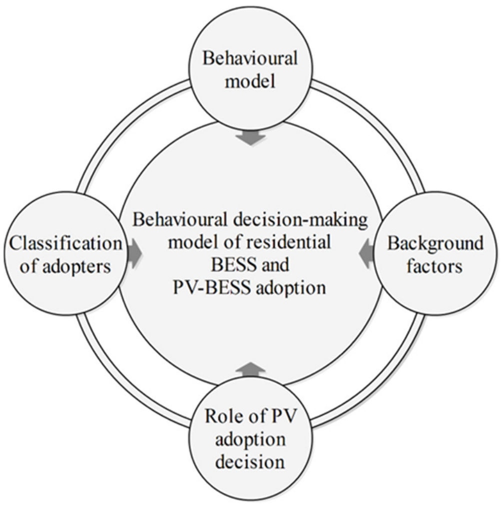


Figure 1. Four fundamental components discussed in this study to build a behavioural decision-making model.

2. Interactions between PV and BESS Adoption Behaviours

The following two sections provide some backgrounds before hypothesising the role of PV on BESS decision.

2.1. Similarities and Differences

The uses of PV and BESS share some discernible similarities. Battery complements the PV system; these systems are closely tied to each other and are energy technology innovations diffused among the residential sector. Their decision models follow the same mainstream, sharing most of the same predictors. Households deal with retailers and energy suppliers with incentives and rebates that are often offered to encourage purchase. They are installed in the house; unlike other technologies, such as hybrid vehicles or energy-efficient technologies, PV and BESS are generally non-transferable [7]. Along with the house and vehicle, these two are of the most significant investments that a person make. They come in different sizes, their use requires physical and non-physical requisites, and their total costs and profitability are the functions of the grid electricity price.

With respect to the existing differences, the solar PV device is an electricity generation system, whereas BESS is a storing tool. The PV system is a more well-known, established technology than the nascent, less-known BESS. The general range of the lifespan of a battery is 5–15 years, meaning that for a new adopter of a solar system, two storage systems are required to match the 25- to 30-year lifespan of PV [8]. For the mature PV markets such as Australia, BESS is in the early stages of maturity and is still relatively unattainable for interested individuals. The techno-economics of BESS rely upon the presence and conditions of PV. The rooftop solar array is also more exposed to visibility by peers, which potentially differentiates the efficacy of interpersonal effects.

2.2. Interrelations between PV and BESS Adoptions

Having PV installed in the house could stimulate the individual to take another step towards self-governance (energy independence). For a grid electricity consumer, BESS is a motivator to utilise PV. However, PV can have an adverse effect on BESS use as well. While solar consumers only pay for the cost of BESS, traditional electricity users need to pay much more to use both systems. This high upfront cost could serve as a major constraint for PV non-adopters or at least change the idea of buying both at the same time (i.e., change in adoption timing) [9]. What seems essential in understanding the intention of the user is that the analysis needs to consider the potential motivation or impediment that one system brings to the study of the technology. This condition applies to PV only when BESS is available at scale.

2.3. Role of the PV Adoption Decision

As the characteristics of PV and BESS adoption behaviours principally arise from the same pattern, there are interrelationships between these two choices and, specifically, the PV decision is the antecedent sequence to the BESS decision. This notion indicates that their adoption archetypes are not necessarily identical but are still very similar in various directions. It can be argued that the decision made regarding rejecting or accepting PV is the past behaviour of the BESS adopter. This proposed proposition does not seek to propose that the paths to PV and BESS decisions are the exact same or that the "past behaviour is the best predictor of the future behaviour" [10] fff. Rather, the role of the PV decision as being the possible consequence of the past choice is emphasised. Subsequently, three attitudinal scenarios can be drawn:

- Regret: An attitudinal feeling that arises from not taking action sooner (i.e., not adopting PV earlier than it should be). Feelings of regret can be a false perception or cognitive consideration. Examples are expecting to move to a new place or anticipating the costs to swiftly decrease. Of course, regret becomes sensible only when earlier adoption would be an option—explicitly, the person had control over the behaviour. In the same condition, it can is likely that the regretful homeowner, happy with consumping the rooftop PV technology, would be an earlier adopter of BESS. This scenario also applies to the rejectors despite their interest. The rejectors could believe that it is too late to act or could be waiting for the simultaneous purchase.

- Stability: The experience of PV consumption contributes to no attitudinal change: whether it be a rejection or acceptance, the decision instigates no favourable or unfavourable belief. Thus, this reverberation is expected to have no attitudinal reverberation for BESS.
- Despair: The feeling of dissatisfaction and discontent. A despairing person is also regretful but from PV acquisition. The consumer tends to be unimpressed by over expectations (e.g., lower bill savings than expected) or technical frustrations. When the despaired consumer compares the financial aspect of adoption timing, he/she may adjudicate that the purchase occurred prematurely. A despairing prosumer hesitates when assessing BESS.

3. Classification of Adopters

The basis of classification is identification—the specification of the similarities and, at the same time, differences among the members of a society [11]. Classification determines intergroup behaviour, which favours the ingroup and discriminates against the outgroup. The literature in the renewable energy context is dominated by the five categories of the Diffusion of Innovation (DoI) theory (Figure 2) [12]. Energy Network Australia also suggests an analogous s-curve-based category for Australian customers in 2027 (Figure 2). The following subsection argues why such classification may not necessarily be precise.

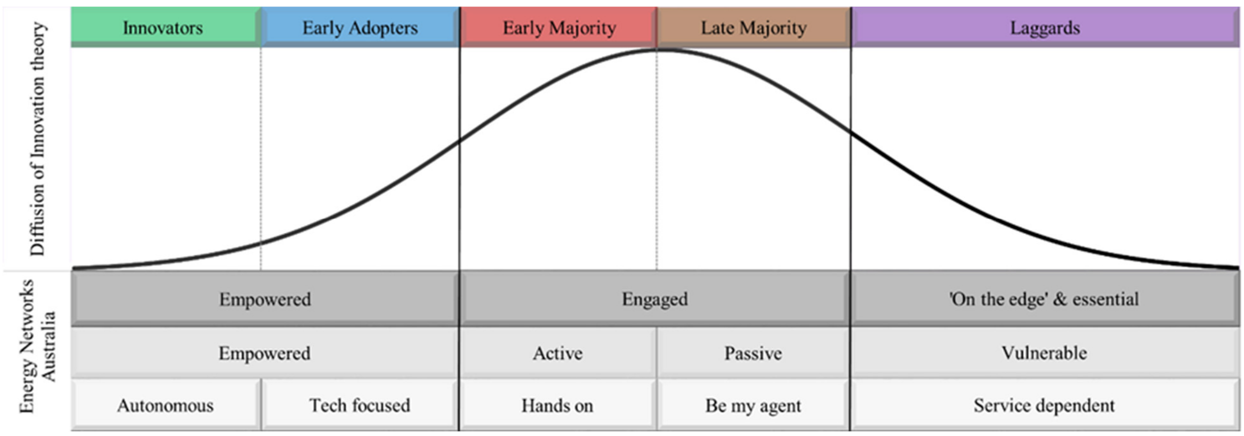


Figure 2. The categorisation of individuals by DoI [12], and Australian households by Energy Networks Australia [13].

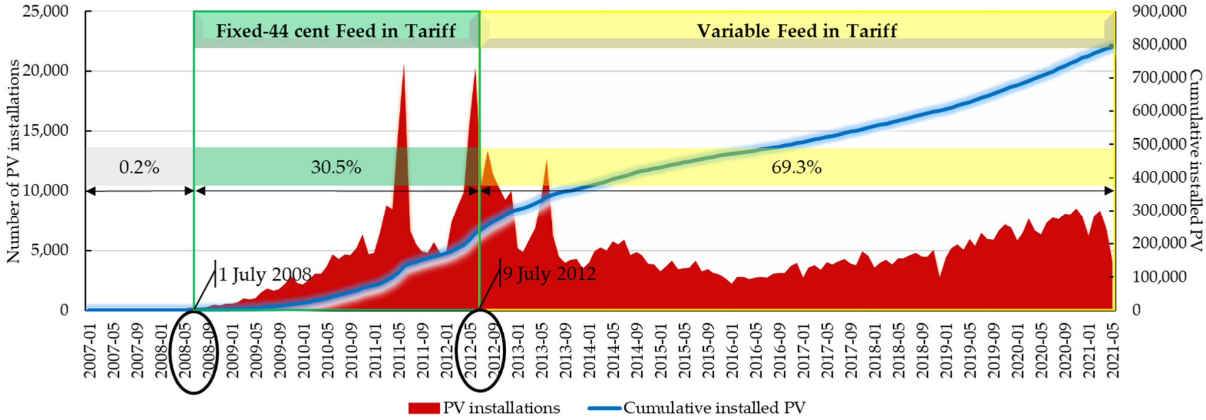
3.1. Categorisation of BESS Adopters

The process towards the identification of favouritisms and discriminations exerts a set of social and individual indicators appraising the foundation of the classification. For innovation and motivation, they are mostly education, age, income, energy consumption, and personal and environmental norms. However, these determinants are not always able to distinguish discriminative behaviours. The research has been unable to correlate several sociodemographic factors of adoption behaviour [1,14]. This inconsistency is more or less the same for individual parameters [15], questioning their practicality in distinguishing power. Luckily, there is an alternative mechanism for the improved categorisation of BESS adopters. Though not by the traditional social and individual indicators, an authenticated classification can be gleaned from the past behaviour (i.e., the adopters' history for the PV decision).

3.2. Categorisation of Queensland Adopters

Queensland homes with a high PV take-up rate need to be categorised not only on the innovation level but also on the PV utilisation and adoption time. Whether a household uses this technology changes the financial details. Meanwhile, a PV user needs to pay only the cost of BESS, a non-adopter should pay for both systems, which is possible at the same time or over a period. To make this more complex, the installation time makes a substantial difference by mixing the economic dimensions. By 9 July 2012, the Queensland Solar Bonus FiT scheme (SBS) guaranteed a 44 c/kWh rate for residential PV buyers (Figure 3). SBS is expected to be in place by 1 July 2028 for those who purchased before that time [16]. However, the scheme was closed to new applicants, and the hodgepodge Feed-in Tariff (FiT) rate was reduced to variable (at the base of 8 c/kWh) for those submitting their applications after 9 July 2012. Today, state-mandated tariffs are no longer available to new installers in almost all of Australia's states and territories, although electricity retailers continue to offer voluntary rates in the range of 6–15 c/kWh [17].

(**a**)



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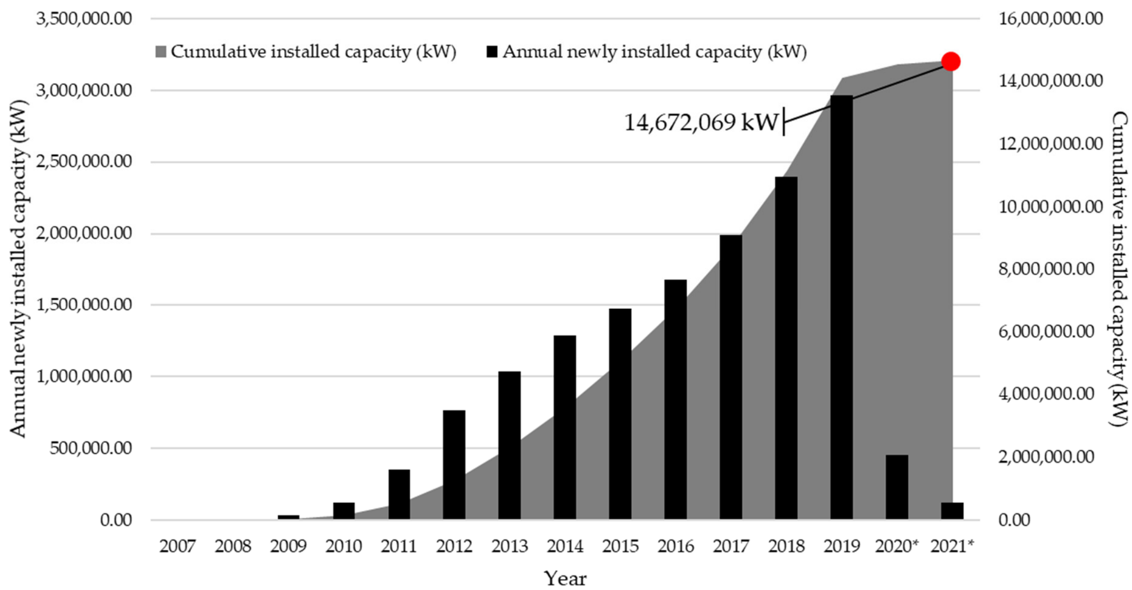

Figure 3. (**a**) The number of residential solar PV installations in Queensland, Australia, by the FiT rate (the percentage refers to the proportion of the adoption rate for each period); (**b**) power capacity from these installations (* the data for 2021 and 2021 are not finalised and represent only the available data) (data adapted from [18]).

The significance of using PV and the installation time falls into the initial cost and payback period time. The initial investment costs between BESS and PV–BESS vary greatly, and the payback period for PV adopters before 9 July 2012 and after this time also differs. For the difference in the payback period, one may argue that the consumers who subscribed to the FiT before 9 July 2012 are likely to wait until 2028 to avoid the loss of income from the exported electricity. This implication suggests that while they are basically innovators, it remains unclear whether they will pose the same enthusiasm for BESS as well. Therefore, the nature of PV epitomises the disruption not only in terms of technology but also for the uptake of BESS. Accordingly, Queensland adopters can be categorised into four groups (Figure 4).

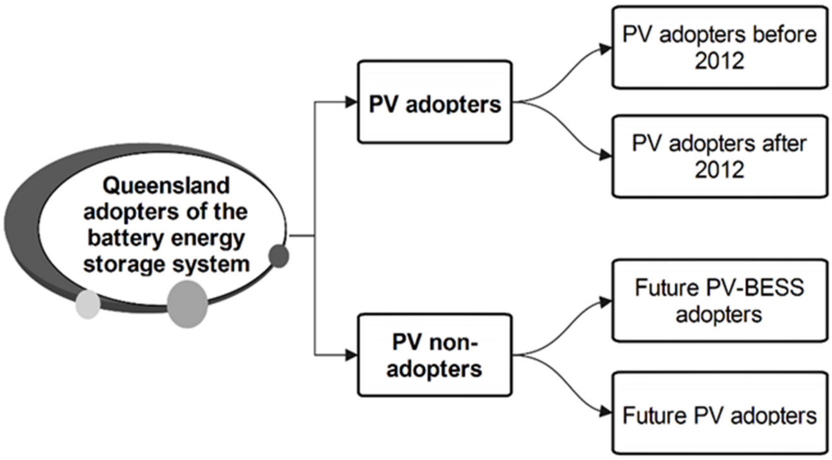

Figure 4. The proposed categorisation of BESS and PV–BESS adopters for Queensland dwellings.

- PV adopters before 2012: Labelled as innovators, PV adopters before 2012 are 'savvy' economic benefit-seekers who strategically timed their purchase to right after the SBS was introduced. They could also be post-materialistic and wide-awake, for which the SBS triggered their decision. They are most commonly found in South East Queensland, currently under contract with the government with a FiT rate of 44 c/kWh until 2028 [19]. The uptake of BESS before 2028 will likely cause a financial loss or a more extended payback period since the electricity will be stored rather than returning to the grid. Although projected to have a stronger intention, they could wait until 2028 to ensure a maximum profit. Aside from their intentions, they are proactive in response to emerging technology.
- PV adopters after 2012: The PV adopters after 2012 constitute another group of current PV users but who are on a yearly contract with the government under a lower FiT. Their characteristics embrace broader features, whether they be early adopters, the early majority, or to some extent, the late majority. Their level of awareness is assumed to be lower than the first group. Alternatively, they hold a higher perceived risk and decided to purchase once their uncertainty was reduced. The government would target this group as the main prosumers, though turning them into innovators will likely not come easily.
- Future PV–BESS adopters: This group adopts both systems at the same time to enjoy the benefits of government incentives. This class can afford the costs of both technologies and has the required infrastructure and capacity, but for some reason, they have refused to opt for PV. A reason could be 'regret', the decision not to act on time. This group could be the potential innovators of BESS. However, as with the first group, the government will likely find it difficult to urge them to invest in both packages, which comes by spending a large amount of money.
- Future PV adopters: The last group comprises current grid electricity users who will install PV in the upcoming years but not BESS right away. Commonly less exposed to peer effects, they come from a lower social class. They can be labelled as the late majority and laggards, who hold similar characteristics to the third group. Once PV is acquired, it will be unclear whether they can afford BESS, thereby making time important for the government to prompt them to become simultaneous buyers.

4. Behavioural Decision-Making Model

Behavioural decision-making models seek to understand how individuals make decisions and are built upon a fundamental postulate that human decisions are rationally bounded [20]. The goal of these theoretical-based models is to design effective interventions to change the behavioural patterns of a group of people in a society. The BDMMs in technology diffusion aim to describe the adoption behaviour, target salient predictors for interventions, and develop a framework for empirical research based on the effectiveness of these interventions.

4.1. Reasoned Action Approach

This work employs the conceptual model based on the RAA, which is incorporated by two established theories (Figure 5): The Theory of Reasoned Action (TRA) and the Theory of Planned Behaviour (TPB). What is clearly distinguished in RAA is the embeddedness and explicit description of the 'actual control' component, detached from perceived behavioural control (PBC) [21]. This inclusion enables pinpointing controlling differentiators that impede a person from acting. The literature on the renewable technology precinct does not differentiate between PBC and actual control [1]. The RAA is also relatively new, comprehensive, and inclusive in encompassing the breadth of decision behaviour. Its constructs are not restricted to psychological factors; unlike other models, such as the Value Belief Norm theory, RAA is open to external predictors that reside outside the psychological domain. The theory posits that intention is the immediate antecedent of behaviour, meaning that a person performs the action if he or she has enough intention [22]. Intention is a function of three primary constructs: attitudes, perceived norms, and PBC towards the behaviour, all of which originate from behavioural, normative, and control beliefs.

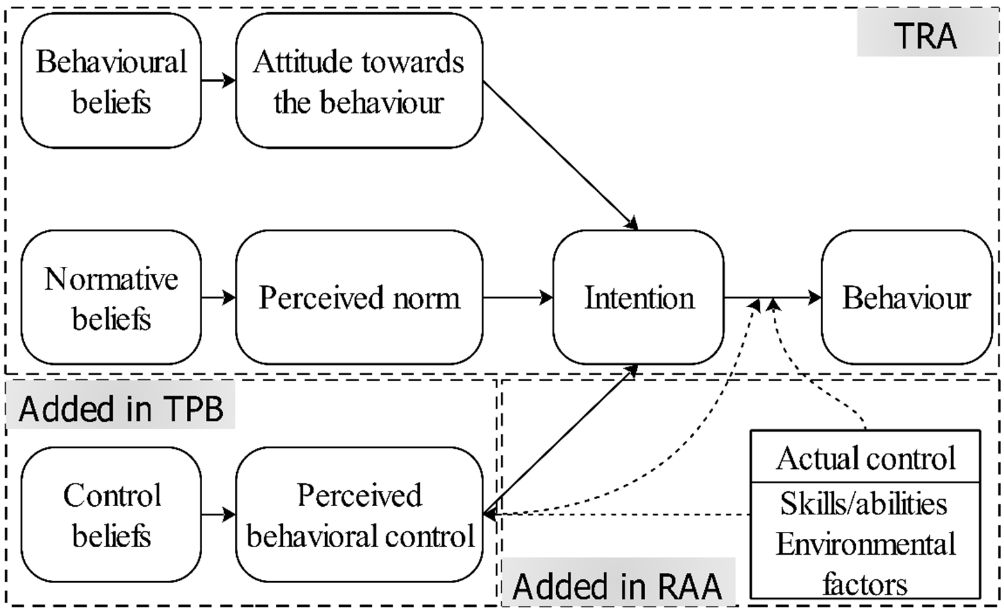

Figure 5. Simplified formation of the Reasoned action model from two other well-known behavioural models [21].

4.2. Background Factors of BESS and PV–BESS Adoption

For Queensland homes, the application of standalone BESS for storing the electricity from only the grid to be used during the peak demand is potentially possible, but it is economically unprofitable and is projected to remain the same by at least 2035 [23]. This limitation in use draws upon a fundamental assumption of this research, which postulates that the uptake occurs if the household is already using electricity from a solar source or just purchases PV–BESS at the same time.

For the residential sector, BESS is perceived as an innovation with both hardware and software components. For adoption, several physical and non-physical requirements must be met. The innovation comes with technical attributes, such as the Depth of discharge

(DoD), capacity and power rating, lifetime, and cycle life [24]. However, what usually dictates the motivation or reluctance is built upon many non-technical factors. These determinants define how the intention, attitudes, and norms are formed and whether there is an obstacle to using the technology. The RAA categorises all non-technical and technical elements into three types: social (or sociodemographic), informational, and individual [22]. The first two types are external and exogenous, while the individual type refers to the endogenous characteristics. At the social level, education, gender, age, employment status, socioeconomic status, and income appraise affordability. The characteristics of the house present significant social parameters of the decision. The physical and non-physical specifications of the building, such as the size, value, type, age, and ownership, reveal the wealth of the family and also measure suitability [25]. For the last two groups, the suitability of the building for using PV must be met as well—that is, the roof type and quality and solar radiation, measured by sunshine hours, tree cover, temperature, weather condition, and building shading, are sufficient for installing panels.

The informational type hints at financial and technical knowledge. The financial attributes reveal how much the total costs and the payback period will be through the electricity cost, installation cost, O&M cost, utility rebates, upfront cost, and importantly, government support policies in the form of the FiT, grant, discount, and tax incentives. The individual type receives financial and technical information from not only the media but suppliers, business, government, and peers [26]. These are five major formal and informal (interpersonal) communication channels for transmitting messages. They increase knowledge and awareness and shape the attitudes. The exposure and trust in these sources define the degree of their impacts on the person's behaviour [27]. The individual type involves all the inner motives, feelings, beliefs, and values that represent perceptions towards the financial and technical features of BESS uptake. Conceiving of financial details can be the perception of the affordability, payback period, government supports, and costs and benefits [28]. The personality (e.g., innovativeness level, risk-taker, or risk-averse), perceived risks, and values indicate the other individual factors. When financial and technical knowledge is received from the communication channels, they are processed and moderated by these perceptions. Psychological factors are of particular interest to intervention designers when changes to the external factors, such as financial details, are restricted to certain extents [29].

5. A Pilot Decision-Making Model

From a holistic view, the involvement of the individual, social, technical, and economic factors is trivial, contributing to the bounded rationality of the final decision. The RAA can conceptually structure and frame a model of BESS and PV–BESS decision behaviour by households (Figure 6). To describe the components, the model is segmented into two parts: attitudinal and control components. The attitudinal part covers three main constructs: the attitude, norm, and attitudinal concept of the PBC. The latter discusses the actual control and the controlling aspect of the PBC.

5.1. Attitudinal Component

The attitude is formed by the individual and social influence factors, each containing a set of sub-factors. The PV past decision can create an attitudinal effect of 'regret', 'consistent', or 'despairing' feelings. The personal dispositions shed light on the beliefs about the expected outcome regarding the economic aspects (e.g., the payback period, future electricity price, and investment costs). The perceived risks correspond to the uncertainty about the efficiency (the technical facet) and financial costs. The values are the other individual factors that highlight the motivation and tendency. However, assessing the extent of the perceived values requires careful consideration since the environmental values of PV and BESS can be different.

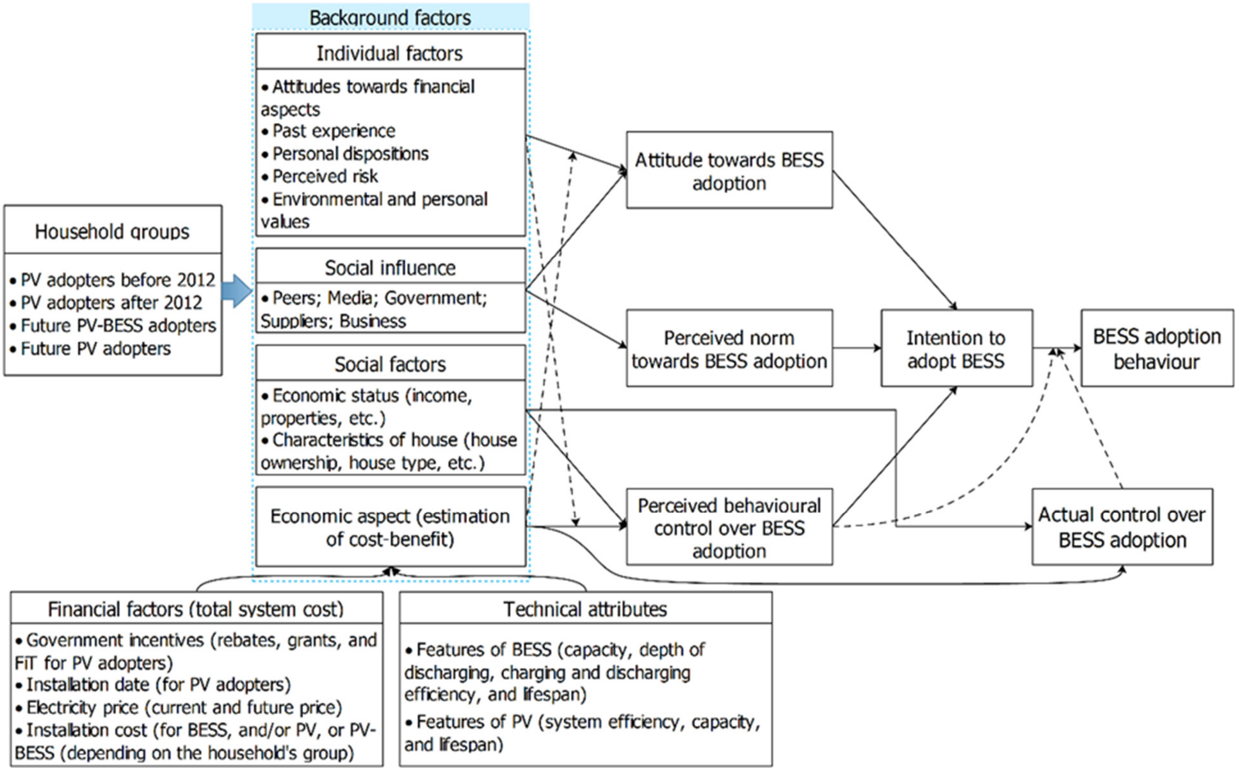

Figure 6. Example of a behavioural decision-making model for BESS adoption.

The perceived norm refers to the social pressure that stems from the media, government, suppliers, and business partners. The range of peers (neighbours, colleagues, family, relatives, friends, media, and retailers) implement pressure on non-users in society. Proven significant peers can also reduce the perceived risks and uncertainty, thus influencing the attitude [30]. However, their influential power impacting both the pressure and risk (or uncertainty) varies depending on the volume of the neighbours in the area, their geographical distance, and their dependence level (independent judgement maker or imitator). With the inevitable rising ubiquity of social media, future online social network interactions are expected to shift the dominance of neighbour peers to non-neighbours [31], and PV users are perhaps more exposed to this paradigm, given the lower visibility of BESS.

PBC elucidates customer perception of whether there is enough financial power. If the belief is that there is enough budget, the control will be high, and there will be a higher intention [32]. PBC does not only originate from economic calculations. In its formation, the actual calculations are moderated by the personal beliefs of the outcome of the action. These personal beliefs can differ based on personal dispositions, such as perceived risks, innovativeness, and other personality traits. The economic estimations are obtained by two data sources: financial and technical attributes. These sources imply the actual payback period and total investment cost. Two data types from the financial factors arise from outside of the technology: government incentives and the future grid electricity price, both of which can significantly alter the calculations.

5.2. Control Component

The controlling role of PBC is the salient economic belief of the person and whether the total cost is within the budget limit. Recalling that, this perception can be different from the facts since there might be, for example, a lack of knowledge about government incentives or different purchase options, such as leasing. If PBC is not met, the person rejects the idea regardless of how firm the intention is. In practice, strong exposure to information channels can assure the acquisition of the required knowledge.

Actual control is the second and central part of the control component of the behaviour which is unveiled from two conditional clauses. The first axiom is a purely economic facet that directly comes from the financial and technical attributes. It assumes that the customers are likely to use the innovation only if they are financially able to do so. There is a subtle difference between PBC and actual control. Illustrative examples with two scenarios are presented as follows. In the first scenario, an individual has strong confidence, though holding the belief that the financial resources are insufficient, regardless of whether the resources are in fact enough (PBC is not met). In the second scenario, a person has a firm intention and does believe the budget is enough (PBC is met), but the actual costs exceed the range, making the person unable to adopt (actual control is not met). The second conditional clause relates to a technical constraint. This clause refers to the primary assumption of the analysis that to use BESS, rooftop PV must be installed. Thus, the behaviour occurs only when PV is being used or when BESS is adopted together with the PV system.

5.3. Characteristics of the Model

Rather than delivering over-detailed background factors that could differ for each geographical area, this study itemised potentially clear-cut elements and structured their linkages to the decomposition of the model components. Broadly, actual control and PBC moderate the effects of intentions, and the intention is expected to be an accurate predictor only when both components are satisfied (i.e., the behaviour is under volitional control). The importance of assessing the controlling parts is self-evident in the economic and technical attributes. Many of the background factors and explanatory constructs evolve over time. This evolution transpires via the intrinsic or extrinsic shifts. For example, intrinsic change emerges in the attitude by interacting with peers. Extrinsic changes can be a decline in the financial limitations or an improvement in the technical attributes (e.g., efficiency or lifespan).

The characteristics of the household groups undertake the formation and magnitude of the background factors. The financial calculations of PV customers and, consequently, control components differ from non-users. Within these groups, the attitudes as a result of PV uptake behaviour and the level of innovativeness and sociodemographic status can differ. An interesting area will likely be the analysis of the possible homophily that might exist between members of an ingroup and the extent of the social interactions or intergroup behaviour occurring between the ingroup and outgroup. In future studies, the presence of two technologies and the wide range of factors provided here might deliver an added complexity to the modelling approaches, such as agent-based models. In building the model, the complexity could be reflected in parameterisation, validation and quantitative analysis stages. One should keep in mind the necessity of selecting the influential variables to avoid ending up with the attenuated impairment in the outcome of the diffusion rates.

6. Conclusions

This short communication sought to elucidate the involved elements in the decision structure of BESS and PV–BESS adoption by households. The formation of the behaviour was exemplified through RAA, whereby most overriding predictors and background factors and their links to the main constructs were scrutinised. It shed light on the differences that exist in other traditional adoption decisions where PV plays an interactive role in the uptake of BESS while segmenting homes into different classes in terms of technology use. The resulting implication would yield a higher degree of heterogeneity but provide more room to policymakers for targeted interventions. How the long-term governmental incentives could unbalance the attitudes of BESS buyers is noteworthy in the role of utilising PV uptake.

The RAA could also suggest that when the requirement is met, even with a strong intention, two conditions govern the final decision: affordability and whether PV is already installed. What seems challenging in modelling and extrapolating the diffusion rate is the inclusion of multiple over-detailed factors, (and exclusion of some elements depending on the status of using solar energy), studying two adoption types at the same time, and the incorporation of PV with BESS consumption. As BESS technology enters the mass market, more research is welcome to understand how to properly direct the diffusion in an equitable manner. If the upcoming scaled BESS diffusion strategy is poorly managed, there will likely be several perverse outcomes comprising social discrimination, low uptake rates, or the creation of winners and losers from government incentives. Consequences occur when the existing gap between PV adopters and non-adopters is further widened to PV–BESS adopters and non-adopters.

Author Contributions: Conceptualization, M.A.; investigation, M.A.; methodology, M.A.; validation, M.A., R.A.S. and O.S.; formal analysis, M.A.; investigation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, R.A.S. and O.S; visualization, M.A.; supervision, R.A.S. and O.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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