01 Jul 2019

Notes on the Economics of Residential Hybrid Energy System

Mahelet G. Fikru
Missouri University of Science and Technology, fikruma@mst.edu

Gregory M. Gelles
Missouri University of Science and Technology, gelles@mst.edu

Ana M. Ichim
Missouri University of Science and Technology, ichima@mst.edu

Joseph D. Smith
Missouri University of Science and Technology, smithjose@mst.edu

Recommended Citation
Fikru, M. G., Gelles, G. M., Ichim, A. M., & Smith, J. D. (2019). Notes on the Economics of Residential Hybrid Energy System. *Energies, 12*(14) MDPI AG.
The definitive version is available at https://doi.org/10.3390/en12142639

energies

MDPI

Review

Notes on the Economics of Residential Hybrid Energy System

Mahelet G. Fikru [1,*], Gregory Gelles [1], Ana-Maria Ichim [1] and Joseph D. Smith [2]

[1] Department of Economics, Missouri University of Science and Technology, Rolla, MO 65409, USA
[2] Department of Chemical and Biochemical Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA
* Correspondence: fikruma@mst.edu

Received: 3 May 2019; Accepted: 6 July 2019; Published: 10 July 2019

check for updates

Abstract: Despite advances in small-scale hybrid renewable energy technologies, there are limited economic frameworks that model the different decisions made by a residential hybrid system owner. We present a comprehensive review of studies that examine the techno-economic feasibility of small-scale hybrid energy systems, and we find that the most common approach is to compare the annualized life-time costs to the expected energy output and choose the system with the lowest cost per output. While practical, this type of benefit–cost analysis misses out on other production and consumption decisions that are simultaneously made when adopting a hybrid energy system. In this paper, we propose a broader and more robust theoretical framework—based on production and utility theory—to illustrate how the production of renewable energy from multiple sources affects energy efficiency, energy services, and energy consumption choices in the residential sector. Finally, we discuss how the model can be applied to guide a hybrid-prosumer's decision-making in the US residential sector. Examining hybrid renewable energy systems within a solid economic framework makes the study of hybrid energy more accessible to economists, facilitating interdisciplinary collaborations.

Keywords: renewable energy; cost benefit analysis; prosumer; price of energy; decision science

1. Introduction

Despite technological advances in small-scale hybrid renewable energy systems, there are very few studies that model the economic decision-making of a household which generates energy from multiple sources. Combining the concepts of energy production and consumption at the residential level, studies in energy economics refer to a household with an energy-generating capacity as a "prosumer" (see Sun et al. [1], MacGill and Smith [2], Green and Staffell [3], and Schill et al. [4]). There are several benefit–cost analyses that examine a prosumer's decision to adopt a single renewable source (examples include Zarte and Pechmann [5], Jung and Tyner [6], and Swift [7]). For example, Ghaitha et al. [8] examine the economics of a residential wind turbine system while Ghaitha et al. [9] and Swift [7] study the economic feasibility of a residential solar panel system. Tervo et al. [10] examine the costs and benefits of a residential photovoltaic system with a lithium ion battery. However, there are only few benefit–cost analyses for hybrid energy systems in the residential sector. Following the literature, we refer to a household that produces and uses energy from multiple sources, including renewables, as a 'hybrid-prosumer'. The system owned by the hybrid-prosumer is referred to as a 'hybrid energy system' (HES) or simply a 'hybrid system'.

This study builds an economic model for hybrid-prosumers. We consider a hybrid system that produces energy onsite from multiple renewable energy sources [11]. The hybrid-prosumer's simultaneous choice on energy efficiency, energy services, and energy consumption is included in the model. First, we derive the effective unit price of energy consumption for three types of hybrid-prosumers (net generator, net consumer, and net zero house). We examine the effect of a mismatch, if any, between production and consumption, on the level of energy consumption and its effective unit price. Second, we study the effect of increasing the number of renewable energy sources on the economically optimal level of energy consumption and explore possible rebound effects from generation. Finally, we use average prices from the US energy market to illustrate how the economic model can be used to guide the decision-making of an average hybrid-prosumer.

Why do residential units adopt a hybrid instead of a single renewable energy system? First, a hybrid system overcomes the inconsistent supply of a single renewable source. For instance, a photovoltaic-wind system is more likely to consistently produce power than a photovoltaic system alone because peak operating times for wind and solar systems occur at different times of the day and year. Thus, rather than wind and solar acting as substitute energy sources, as a hybrid system they could create synergy in the production of electricity [12]. The potential for generating electricity when needed will be higher with hybrid than a single energy source.

Second, a hybrid system can be integrated with an energy storage technology, providing a reliable back-up when and if consumption exceeds production. Energy storage can help reduce the size of other components (e.g., photovoltaic panels or wind turbines) and cut down costs. According to the US Department of Energy [13,14], most residential wind–solar systems can operate off-grid by providing power through batteries when the renewable component is not producing. Others may be connected to the grid via a smart grid allowing the homeowner to measure the electricity sent back to the grid [15,16]. Third, for remote locations, off-grid hybrid systems are cost-effective compared to extending the power line [16]. Finally, a HES can meet demand for energy with a lower environmental footprint and contribute to a distributed and diversified energy infrastructure [17].

A unifying aspect of the arguments presented above is the existence of the so-called technological gap. This gap is defined by Shove [18] as the difference between "current practice and recognized technical potential" and by Jaffe and Stavins [19] as the difference "between actual and optimal energy use". In essence, the technological gap reflects a failure to optimize that has been identified in engineering studies as a slow transfer of technology; in economic analysis, as the result of market and non-market failures; and in psychological literature, as cognitive dissonance. In this paper, we use an economic model, based on production and utility theory, to address this issue in the context of a hybrid residential energy system. Our goal is to gain insight into the decision-making process of the hybrid-prosumer.

Several projects all over the world have demonstrated the application of small-scale hybrid energy technologies. For example, Frostburg State University in Maryland, US showcases a grid-tied residential size solar–wind system [20]; Yuan Ze University in Taiwan owns a small-scale photovoltaic–wind–fuel cell system [21]; and Pamukkale University in Turkey demonstrates a hybrid photovoltaic–hydrogen fuel cell–battery system designed to meet demand from non-fossil fuels [22]. In recent years, commercial HES developers have introduced products targeting the residential sector [12]. For example, WindStream Technologies Inc. is a US based developer of renewable energy generation products. Since May 2015, the company has commercialized a 1.2 kW system of solar panels and wind turbines that are suitable for grid-tied residential installations [23]. Another example is General Electric Company which has recently commercialized a solar–wind and a hydro–wind system in several countries including the US [24]. According to an industry research report conducted by Global Market Insights Inc. and authored by Gupta and Bais [25], the global hybrid solar–wind market was valued at $700 million in 2015 where the US market accounts for close to 28%. The report also finds that, from 2013 to 2015, the generation of energy from standalone or grid-connected hybrid solar–wind installations in the US has increased by 24% [25]. Given that hybrid energy technologies have a solid emerging demand, it is timely to consider their impact on other energy-related decisions such as energy-efficiency, energy services, and energy consumption.

In the following section, we present a summary of past studies which examine the technological and economic feasibility of a HES. In Section 3, we introduce a theoretical framework to understand the several layers of decision-making that a typical hybrid-prosumer faces. We consider three types of hybrid-prosumers: net energy generator, net consumer, and a net zero house. In Section 4, we present discussions and examine insights gained from the model.

2. Techno-Economic Studies on HES

Studies on the financial and economic feasibility of residential HES are widely dispersed across many engineering and energy focused journals. Despite the substantial research on the techno-economic analysis of residential HES, economic approaches have been restricted to cost-analysis. Deshmukh and Deshmukh [26] find that cost analysis is the most popular tool used to select among different types and sizes of HES. Specifically, the life-cycle cost of a system is calculated as the present value of life-time costs. Life-time costs include initial installation (e.g., component and system cost), replacement cost (e.g., batteries and/or inverters may need to be replaced), and operating and maintenance cost less any salvage value. Typically, calculations are made on an annual basis and the life-times assumed for the systems differ widely across studies [27,28].

Many studies rely on the calculation of the levelized cost of energy (LCOE) as an indicator for the financial performance of a small-scale HES. The LCOE is usually computed as the ratio of the total annualized cost of a system to either the annual electricity generated by the system or the annual electricity consumed by the household. The present value of life-time cost is divided by the capital recovery factor to find total annualized cost. A system with the lowest LCOE is considered to be cost-effective relative to others [27,28]. In the following paragraphs, we present a discussion of a few representative studies that apply the LCOE method in the analysis of a small-scale HES.

Li et al. [29] present a techno-economic analysis of three types of stand-alone systems for a typical household in Urumqi, China. A typical household is defined as a two-bedroom house with three people. The three systems are a hybrid photovoltaic–wind–battery system, a photovoltaic–battery system, and a wind–battery system. The photovoltaic–wind–battery system is composed of a 5 kW of photovoltaic arrays, a wind turbine of 2.5 kW, eight unit batteries each of 6.94 kWh, and a 5 kW power converter. The authors calculate and compare the LCOE of the three systems by taking the ratio of total annualized cost of a system divided by annual electricity consumption. They find that the photovoltaic–wind–battery system has the lowest LCOE of $1.045 per kWh of electricity consumption. The photovoltaic–battery and wind–battery systems' LCOEs were calculated as $1.150 and $1.173 per kWh respectively. The photovoltaic–wind–battery system reduces the need for a larger battery because the two energy sources, solar and wind, often complement each other: when one is at a lower supply the other is usually at a higher supply. Ashok [30] calculates LCOE in a similar fashion as the ratio of total annualized cost to total electricity consumption. He finds that a micro-hydro–wind system with a small battery backup provides the lowest LCOE of Rs 6.5 per kWh of load served to an Indian rural village. Likewise, Shaahid and Elhadidy [31–33] perform a techno-economic assessment of a grid independent photovoltaic–diesel–battery system in Saudi Arabia. The cost of generating energy from the system is calculated to be $0.149/kWh [31].

Lv et al. [34] assess the techno-economic feasibility of a photovoltaic–wind–storage system owned by a Chinese household in Hangzhou, Zhejiang Province. Based on the household's annual energy use of 5935 kWh and local weather data, the authors find a 5 kW photovoltaic panel, 7 kW wind turbine, 5760 Ah battery, and a 6.2 kW converter system to be optimal for the household. Even if the specified hybrid system produces excess energy in aggregate, there is a 0.86 percent unmet load in the months of February and August (due to heavy load and maximum discharge depth of battery). This illustrates that even if a hybrid system significantly reduces the mismatch between consumption and production, it may not completely eliminate it. The system's calculated LCOE is $0.146 per each kWh of electrical energy generated by the system. This is less that the local retail price of electricity ($0.08 per kWh). With the possibility of selling all excess energy back to the grid, the system can generate $8079 over 25 years, with an adjusted LCOE of −$0.062/kW. Since electricity purchased from the grid is generated in thermal power plants, by providing almost all the energy needs of the household, the specified system contributes to reducing pollution. The authors use local emission coefficients (emissions per kWh) to calculate the annual average savings of atmospheric pollutants attributable to the system and consider this as an environmental benefit.

Diaf et al. [35] study the sizing and techno-economical optimization of a stand-alone photovoltaic–wind–battery for typical residential houses located in three different sites in Corsica Island, a region of France. The three sites have similar solar radiation but different wind potentials. The authors calculate LCOE as the ratio of the total annualized cost of the system to the annual electricity delivered from the photovoltaic arrays and wind turbines. They find that for a given battery size, the LCOE of the system decreases with an increase in load up to a certain load size, after which the decrease becomes very small. For instance, for a three days battery capacity the average LCOE for the three regions is $2.68/kWh for a one kWh of load and the average LCOE is $1.513/kWh for a 10 kWh of load. They also find that, for a given load, a change in battery capacity generally affects the LCOE positively. Ani [36] calculates the present value of costs associated with a photovoltaic–diesel–battery system (15 kW photovoltaic array, 21.6 kWh worth of battery storage, and a 5.4 kW generator) in a remote off-grid house located in Nigeria. Besides the most common cost items, the author estimates the emission cost of the system. The study shows that even if a photovoltaic–diesel–battery system has a higher initial capital cost, the present value of its life-time cost is lower than that of a diesel–battery system. This is because including solar energy in the system reduces fuel consumption and the need for larger batteries. In addition, emission costs are higher when the operating hour of the diesel generator is higher.

Unlike Li et al.'s [29], Ani's [36], and Diaf et al.'s [35] cost analyses, Syed et al. [37] focus on identifying and monetizing the annual benefits of a photovoltaic–wind system for a representative house in Canada. The system generates a total of 7720 to 8832 kWh of energy annually, but since it does not have storage, excess energy is sent back to the grid. They find that the photovoltaic–wind system generates $381.7 CAD annually in electricity bill savings and $340.7 CAD annually in credit for sending surplus energy back to the grid. The study also finds that a house with the photovoltaic–wind hybrid system generates 56% less greenhouse gases compared to a fully grid-dependent house. This is because greenhouse gas emissions from the generation of electricity at fossil fuel-based plants are reduced with the hybrid system, due to the reduction in the electricity import from the grid. More benefit–cost studies are needed to comprehensively evaluate the economic costs and benefits of adopting HES in the residential sector.

The LCOE is an approach that can be used to rapidly evaluate different types and sizes of HES; it has practical applications for the hybrid energy industry. However, it has several drawbacks when used to evaluate a household's energy decision-making process. First of all, according to Bazilian et al. [38], the metrics used in the economics of renewable energy production are not standardized because they are defined in different ways based on the type of available data. For example, in Diaf et al. [35], LCOE is defined as the ratio of total annualized cost to the annual electricity delivered from the photovoltaic arrays and wind turbines; in Li et al. [29] the LCOE is defined as the ratio of total annualized cost to annual electricity consumption.

Second, cost-analyses simplify the hybrid-prosumer's decision-making to choosing the least cost option. Options are either framed as hybrid versus a single renewable energy source (e.g., photovoltaic–wind–battery versus photovoltaic–battery), or different types of HES (e.g., photovoltaic–wind–battery versus hydro-wind–battery). However, when a hybrid-prosumer considers the adoption of a HES, he/she is actually making several other decisions simultaneously or close to each other. These other decisions may have a confounding effect on the choice of the type and size of a given system. In addition, the adoption of a HES with a specific combination of renewable sources may affect the hybrid-prosumer's other energy-related decisions. In the following paragraphs, we discuss three other relevant decisions that are not fully captured by a cost-analysis. These are energy efficiency improvements, energy service production and consumption, and the level of energy consumption.

Energy-efficiency improvements: For the residential sector, demand for energy efficiency and the market for renewable energy generation are not independent. Oftentimes, when households consider onsite generation of a renewable energy, they also consider improving the energy efficiency of their homes [39]. For example, in California a majority of solar photovoltaic homeowners upgraded the energy efficiency of their homes and/or appliances before, or in conjunction with installing solar photovoltaic panels [40]. Thus, one can think of energy generation as a demand shifter in the market for energy efficiency. In the context of policy-making, McAllister [41] argues that both energy efficiency and renewable energy programs are needed to achieve a net zero energy objective.

Energy services: Another important factor for hybrid-prosumers is the level of energy services they can produce from their investments in energy. Fell [42] defines energy services as "those functions performed using energy which are means to obtain or facilitate desired end services." The most common examples of energy services include space heating, cooling, lighting, water heating, and refrigeration. Hybrid-prosumers are producers of energy services in a sense that they transform energy (renewable and non-renewable sources) into energy services by using conversion technologies such as furnaces, space heaters, and pumps [43,44]. Hybrid-prosumers also derive utility from the consumption of energy services and their demand for such services is directly affected by the amount and type of energy used as an input. The implicit value of energy services rarely enter into cost-analyses such as the LCOE.

Energy consumption: The decision to adopt an onsite energy generating system may directly affect energy consumption in the residential sector. After households invest in an energy generating system, such as a HES, they may exhibit a different load profile. On the one hand, households may increase energy consumption post-generation similar to the rebound effect of energy-efficiency [45,46]. According to the rebound effect, improvement in the technical efficiency of technologies reduces the shadow price of energy services, which in turn increases demand for energy input. With respect to renewable energy generation, this implies that renewable generation may reduce the marginal or average cost of energy input, and hence increase its use. McAllister [41] argues that this is entirely due to an income effect, where households "facing reduced total and/or marginal cost of electricity due to the installation of an energy generating system would, in theory, increase overall electricity consumption (presumably prioritizing those end uses with the highest marginal utility)." The income effect indicates redistribution of the savings from the electricity bill to the overall use of more energy.

Based on large dataset from San Diego, California, McAllister [41] finds that the overall electricity consumption trend among solar photovoltaic adopters is that long-term consumption (two and three years post-generation) may be higher than consumption before generation. McAllister [41] finds that this increase in energy consumption post-generation is not very large overall (less than 5%), and although it is hard to determine causation it is observed for households which install relatively large sized generation systems. Such households are "more interested in covering most or all of their consumption and may not be interested in reducing consumption, or may also be involved in home expansion or other energy intensive activities" [41]. Fikru et al. [47] find that energy consumption of a prosumer could be higher than the energy consumption of a comparable grid dependent household. This is because households that generate energy have a lower valuation for energy services because of their ability to generate energy onsite. Lower shadow price for energy services implies higher demand for such services which requires higher energy input, keeping other factors constant. On the other hand, after adopting an onsite energy generating system, the household may decrease energy consumption. For example, the household may make efforts to coordinate the timing of generation with consumption. Energy storage may also contribute to the most efficient use of energy.

It is worth noting that when it comes to residential energy use and the decision-making process of a household, there has always been an interest in improving energy efficiency, increasing technological transfer, and modeling consumer behavior so as to identify behavioral drivers that can be targeted through policy intervention. While the reasons may have changed over time, from reducing dependency on increasingly pricier exhaustible natural resources (oil, gas, or coal) to reducing the household's carbon footprint in order to limit climate change, the research on the determinants of household behavior when it comes to energy use has remained topical. Wilson and Dowlatabadi [48] present a critical review of research done on this subject from four perspectives: conventional and behavioral economics, technology adoption theory, and attitude-based decision-making, social and environmental psychology, and sociology. They advocate for integrating research findings across disciplines and they underline the difficulty of developing an all-encompassing model. One challenge is to reconcile the individually centered decision models (economics, psychology) with the social construction of technology, energy use, and climate. The second is the trade-off between the need to understand behavior (which increases model complexity), and the purpose of designing and evaluating policies (requires simplicity). The authors' suggestions are threefold: recognize the existence of heterogeneity, especially when moving from individual to social level of decision; match the models to decision types and contexts; and consider the use of nested decision models.

Stern [49] stresses the need for interdisciplinary, collaborative efforts when it comes to developing realistic behavioral models designed to understand household behavior in the context of energy. He discusses the necessity of contextualizing the problem, identifying the barriers to changing behavior and targeting it by using combined approaches that incorporate financial incentives and non-financial features (feed-back, communication of information), which psychology can help with.

In the following section, we develop an economic model for the hybrid-prosumer by directly capturing demands for energy-efficiency, energy consumption, and energy services while accommodating for the possibility of selling excess energy (if any) back to the grid.

3. Introducing an Economic Theoretical Foundation for a Residential HES

In this section, we present a theoretical approach that can be used to evaluate the economic decision-making of a representative rational hybrid-prosumer. Following Sun et al. [1], we set up an economic model for distributed energy prosumers, but instead of maximizing a utility function based on power load, the prosumer optimizes a utility that depends on energy services, as in Sanstad [50] and Fikru et al. [47]. Relative to the existing literature, the model presented here allows for multiple sources of renewable energy instead of one, and it formalizes the levels at which the hybrid-prosumer needs to make production and consumption related decisions. We consider the cases in which the HES does and does not include an energy storage component. We assume a one-time decision making for a given billing cycle, we solve the prosumer's optimization problem and we discuss how the production of renewable energy from multiple sources affects energy-efficiency, energy services, and energy consumption choices of the household. In the model, variables are normalized for size (e.g., per square foot of living space) and indicate long-run average values (e.g., monthly averages over many years).

The variable E is used to represent the amount of energy consumed, generated, or the level of energy services demanded. Energy is considered for a given billing cycle, such as a month, so the unit of measurement is kWh per month. We use different sub-scripts to differentiate between energy generation (E_G), energy consumption (E_c), and demand for energy services (E_u). Energy generation (E_G) is defined as the total amount of energy generated onsite by using all energy sources. E_g is the amount of energy generated from the gth energy source, where $E_G = \sum_{g=1}^{G} E_g$. We consider G number of renewable energy sources, where $g = 1, 2, 3, \ldots, G$. For example, $g = 2$ represents two renewable energy sources: solar and wind, or hydro and solar. The average cost of generating renewable energy from the gth source is given as c_g, and the total cost of energy generation is given as $\sum_{g=1}^{G} c_g E_g$.

Energy consumption (E_c) is defined as the total amount of electricity consumed or used by the hybrid prosumer. The household derives utility from the consumption of energy services (E_u), not from the consumption of energy itself [43,44]. The objective of the household is to achieve at least a certain minimum level of comfort. A maximum level of comfort is achieved when all energy needs are satisfied, beyond which there is no gain to utility. The household continues to get more utility from more energy services until this maximum level of comfort is achieved. Therefore, the utility function is non-decreasing in the level of energy services.

Furthermore, the utility function is concave in the level of energy services. This happens because the household gets more additional comfort from a one unit increase in energy services when the level of energy services is lower, than when the initial level is higher. This implies there is diminishing marginal utility from the consumption of energy services. We use the following utility function to describe the level of satisfaction or comfort the household derives from consuming energy services. For simplicity, utility derived from all other goods is assumed to be separable and independent from energy services.

$$U(E_u) = \begin{cases} \frac{(E_u - \overline{E}_{u,\min})^{\alpha}}{\alpha}, & \overline{E}_{u,\min} \le E_u < E_{u,\max} \\ U^{\max}, & E_{u,\max} \le E_u \end{cases} \quad (1)$$

$U(E_u)$ stands for the level of utility achieved and it depends on the level of energy services. $\overline{E}_{u,\min}$ is the minimum acceptable level of energy services, and $E_{u,\max}$ is the level of energy services that generates the highest utility, and any increase above does not generate additional utility. $0 < \alpha < 1$ to ensure diminishing marginal utility. Using a different utility function, such as a Cobb–Douglas function as in Fikru et al. [47], does not alter the major implications of the model.

Energy, whether it is purchased from the grid or produced onsite, is transformed into energy services by using energy-conversion technologies such as furnaces, space heaters, and pumps. The household owns an energy-conversion technology with an efficiency rating denoted by β. The amount of energy services derived from a given amount of energy directly depends on the efficiency of the technology. Following, Sanstand [50] and Guertin et al. [43], the relationship between energy consumed, energy services, and the efficiency of a given technology is presented as $E_u = \beta E_c$ where β is the technical efficiency of the technology and $\beta \in (0, \beta_{\max})$. The cost of buying a conversion technology with a β efficiency rating is given by $\beta^2/2$, where the cost function is continuous, non-decreasing, and strictly convex in β [47]. This means that a one unit increase in efficiency costs more on the margin if the initial level of efficiency is relatively high compared to the case where the initial level is low.

The basic model framework is presented in Table 1. As the table shows, there are three levels in the model at which the hybrid-prosumer needs to make decisions: (1) production of energy from multiple renewable sources; (2) production of energy services from energy and energy conversion technology as inputs; and (3) the consumption of energy services.

Table 1. Household's decision-making levels.

Decision-Making	Inputs	Output
Level 1: Production of renewable energy	G number of renewable energy sources	$E_G = \sum_{g=1}^{G} E_g$
Level 2: Consumption of energy and production of energy services	1. Energy purchased from grid or produced onsite 2. Energy conversion technology	$E_u = \beta E_c$
Level 3: Consumption of energy services	Energy services	$U(E_u)$

The application of standard economic theory to the production and consumption of energy requires considering the unique nature of distributed energy generation, which is the possible mismatch between energy generation and energy consumption. Energy generation from renewable sources, such as solar and wind, depends on the weather and the time of the day/night which are factors outside the control of the hybrid-prosumer. Even if a hybrid system overcomes some of the variability in production when compared to a single renewable energy source, we can still expect some level of seasonality in the production of renewable energy. This may create periods during which peak generation is not matched by peak demand. Because of this mismatch, the hybrid-prosumer needs to consider energy storage (battery) and net metering policies with their additional tradeoffs, such as selling back excess energy versus storing it for later use.

We define a as the percentage of consumption derived from instant generation, while $1 - a$ is the percentage of consumption derived from the other two sources, namely, energy storage, and the grid. This way, a captures how well consumption is matched with generation, where $a \in [0, 1]$. For instance, if $a = 100\%$, it means there is a perfect match between generation and consumption; the hybrid-prosumer does not need to buy energy from the grid. Since we have a one-period model, the household will send any excess energy back to the grid for some compensation. If $a = 50\%$, only half of the hybrid-prosumer's energy consumption is satisfied from onsite instant generation. The remaining consumption is satisfied either from the battery (if $E_G \geq E_c$), or by buying electricity from the grid (if $E_G < E_c$).

We consider the parameter a to be exogenous because the household has limited control over the timing of production (e.g., limited generation in a cold evening when the household needs to heat the house, etc.). Although a is exogenous, having multiple energy sources is likely to reduce the mismatch between consumption and production by reducing the variability of production and ensuring production is at a steady rate. For example, there will be less of a mismatch between consumption and generation (higher a), if the household owns a PV–wind–battery system than just a PV–battery system. This implies that, as G increases we can expect the value of a to increase.

The retail price of electricity, in dollars per kWh, is denoted by λ_b. Net metering policies allow the household to instantly send any excess energy back to the grid for which the household is compensated at a rate of λ_s dollars per kWh [51]. We refer to this as the buy-back rate. Some states require utility companies to compensate prosumers at the full retail price of electricity ($\lambda_b = \lambda_s$), whereas other states allow utility companies to compensate at a lower rate ($\lambda_b \geq \lambda_s$).

The hybrid-prosumer may own an onsite energy storage system such as lead acid, lithium-ion or nickel cadmium batteries [52]. The average cost of purchasing and installing the energy storage system is given as c_s dollars per kWh of energy storage capacity. Once the household determines the storage capacity it needs, it will purchase and own it. We assume that any energy which is not instantly consumed will either be stored for use within the billing cycle or sent back to the grid. The same amount of energy that enters the battery (charging) is discharged within the given cycle, and either used to satisfy demand or sent back to the grid. We assume no energy is lost when charging and discharging the battery, but the process involves additional cost. We assume the average charge–discharge cost to be constant and equal to f dollars per kWh. This charge–discharge cost can be considered as a degradation rate of the battery, where the maximum capacity of the battery decreases over its lifetime due to a number of factors, the main one being the number of charge/discharge cycles undergone [53].

Given the above assumptions, we consider the following three general cases. For each case we present the net expenditure of the hybrid-prosumer with and without an energy storage system.

1. Net generation with and without energy storage ($E_G > E_c$)
2. Net consumption with and without energy storage ($E_G < E_c$)
3. Net zero house with and without energy storage ($E_G = E_c$)

For each of these cases, we present and discuss the hybrid-prosumer's three levels of decision-making (see Table 1). First, the household decides how much energy to generate relative to consumption. This is a sizing decision, in particular the sizing of the HES. Using economic principles, the hybrid-prosumer decides how much energy to produce from each renewable energy source. Second, we consider the hybrid-prosumer's production of energy services by choosing the optimal level of energy consumption and energy-efficiency. Furthermore, we take into account the conditions under which the ownership of an energy storage is economically optimal. Finally, we look at the hybrid-prosumer's consumption of energy services. In the following three sub-sections, we present the three cases respectively and discuss each of the outlined decisions.

3.1. Net Generation with and without Energy Storage

If $E_G > E_c$, there is net excess production of energy onsite. Since there is only one period the hybrid-prosumer sells the excess energy for some compensation. We first consider the case where the household has an energy storage with the HES and then present the case where there is no energy storage.

3.1.1. Case 1: With Energy Storage

An energy storage system allows a one hundred percent of energy consumption derived from self-generation. The hybrid-prosumer does not need to purchase any energy from the grid and it has a zero electricity bill. Let aE_c represent the portion of energy consumption satisfied through instant generation and the remaining $(1-a)E_c$ is derived from the battery through charge–discharge. The household needs an energy-storage unit which has a maximum storage capacity of $(1-a)E_c$. The total cost of buying and installing the battery is $c_s(1-a)E_c$ and the total cost of using the battery (charging–discharging) is $f(1-a)E_c$. The household earns $(E_G - E_c)\lambda_s$ dollars from selling excess energy back to the grid.

The objective of the household is to minimize net expenditure with respect to the choice variables (β, E_c, E_g), subject to the efficiency constraint, $E_u = \beta E_c$, and the generation constraint, $E_G = \sum_{g=1}^{G} E_g$. We ignore all the non-negativity constraints for brevity. The Lagrangian function for this problem is given as

$$L(\beta, E_c, E_g, \eta) = \sum c_g E_g + (f + c_s)(1-a)E_c - (E_G - E_c)\lambda_s + \beta^2/2 + \eta(E_u - \beta E_c) \quad (2)$$

The Lagrangian multiplier represents the shadow price of energy services. This is because the price of energy services is not directly observed from the energy market [43,50]. The first order conditions are

$$\begin{aligned}
\frac{\partial L(.)}{\partial \beta} &= \beta - \eta E_c = 0 \\
\frac{\partial L(.)}{\partial E_c} &= (f + c_s)(1-a) + \lambda_s - \eta\beta = 0 \\
\frac{\partial L(.)}{\partial \eta} &= E_u - \beta E_c = 0 \\
\frac{\partial L(.)}{\partial E_1} &= c_1 - \lambda_s = 0 \\
&\;\;. \\
&\;\;. \\
&\;\;. \\
\frac{\partial L(.)}{\partial E_g} &= c_g - \lambda_s = 0
\end{aligned} \quad (3)$$

Using the first order conditions, the conditional demand functions (demand as a function of energy services,E_u) can be derived for β, E_c, and E_g. A few notes need to be made when it comes to the optimality conditions. First, since $\lambda_s = c_1 = c_2 = \ldots = c_g$, the household produces renewable energy at the point where the average cost of generation from all energy sources is equalized to the buy-back rate. Second, since efficiency and energy consumption are considered inputs for the production of energy services, the technical rate of substitution between efficiency and energy consumption must be equal to the relative input prices. The effective per unit price of energy consumption ($P_{EC,1}$ stands for effective price of energy consumption in Case 1) is equal to the added up cost of storage for the fraction of energy that passes through the battery, and the opportunity cost of consumption, which is the buy-back rate. The unit price of efficiency (P_{EE} stands for price of energy efficiency) is simply the marginal cost of the energy-efficiency technology. More formally, the following condition holds

$$\frac{\partial E_u/\partial E_c}{\partial E_u/\partial \beta} = \frac{\beta}{E_c} = \frac{(f + c_s)(1-a) + \lambda_s}{\beta} = \frac{P_{EC,1}}{P_{EE}} \quad (4)$$

For a given level of energy services, solutions can be derived from

$$E_c = \left[\frac{E_u^2}{P_{EC,1}}\right]^{1/3} \qquad \beta = [P_{EC,1}E_u]^{1/3} \qquad \eta = \left[\frac{P_{EC,1}^2}{E_u}\right]^{1/3} \quad (5)$$

where $P_{EC,1} = (f + c_s)(1 - a) + \lambda_s$. When the effective per unit price of energy consumption ($P_{EC,1}$) increases, the household will decrease energy consumption and increase the efficiency level of its energy-conversion technology. Plugging these optimal values into the expenditure function simplifies it as follows: $P_{EC,1}E_c + \beta^2/2$. The first term is the total cost of energy consumption, and the second term is the cost of the energy-efficiency technology. This highlights the role of energy-efficiency decisions for a hybrid-prosumer's expenditure.

In order to find the utility maximizing level of energy services, we maximize the utility function presented in Equation (1) subject to the hybrid-prosumer's budget constraint. The household's income level is represented by I, and it should equal total net expenditure. Solving the entire problem yields the following closed form solutions

$$E_u = \frac{(I/1.5)^{3/2}}{P_{EC,1}} \qquad E_c = \frac{(I/1.5)}{P_{EC,1}} \qquad \beta = [I/1.5]^{1/2} \qquad \eta = [I/1.5]^{-1/2}P_{EC,1} \tag{6}$$

As $P_{EC,1}$ increases, both the demand for energy consumption and the demand for energy services decline. Nevertheless, the rate of change in energy services is higher than the rate of change in energy consumption. That is, $\partial E_u/\partial P_{EC,1} > \partial E_c/\partial P_{EC,1}$. One can also check that there is a positive relationship between the shadow price of energy services and $P_{EC,1}$: as the effective per unit price of consumption increases, it leads to a higher shadow price of energy services, which in turn reduces demand for such services.

3.1.2. Case 2: Without Energy Storage

This case is identical to Case 1 with the exception that the hybrid-prosumer does not own an energy storage system. With zero storage capability, the amount $(1 - a)E_c$ needs to be bought from the grid, where the electricity bill is equal to $(1 - a)E_c\lambda_b$. The household's net expenditure is $\sum c_g E_g + \lambda_b(1 - a)E_c - (E_G - aE_c)\lambda_s + \beta^2/2$. We minimize net expenditure subject to the generation and efficiency constraints. First order conditions are the same as in Case 1, except for the partial derivative of the Lagrangian function with respect to energy consumption which is now

$$\frac{\partial L(.)}{\partial E_c} = \lambda_b(1 - a) + a\lambda_s - \eta\beta = 0 \tag{7}$$

$P_{EC,2}$ is defined as the effective per unit price of energy consumption in Case 2. It is the added cost of buying energy from the grid (for the fraction of energy that is purchased from the grid), and the opportunity cost of consumption (for the portion of energy that is consumed), which is equal to the buy-back rate. We have $P_{EC,2} = \lambda_b(1 - a) + a\lambda_s$, and the solutions presented in Equations (4)–(6) are adjusted by using $P_{EC,2}$ instead of $P_{EC,1}$.

If $\lambda_b > c_s + f + \lambda_s$, then $P_{EC,2} > P_{EC,1}$, and energy consumption in Case 1 will be higher than energy consumption in Case 2. Note that this condition suggests a retail price for the energy, λ_b, that is higher than the average economic cost of storage (the added average costs of installation—c_s, depreciation—f, and the buy-back rate—λ_s, which is an opportunity cost of storing the energy instead of selling it back to the grid). We can also rewrite the condition as $\lambda_b - \lambda_s > c_s + f$ and interpret it as having a difference between the retail price of energy and the buy-back rate that is higher than the average hardware cost (installation and depreciation).

If $\lambda_b < c_s + f + \lambda_s$, then $P_{EC,2} < P_{EC,1}$, and energy consumption in Case 2 will be higher than energy consumption in Case 1.

If $\lambda_b = c_s + f + \lambda_s$, then $P_{EC,2} = P_{EC,1}$, and energy consumption in Case 1 will be identical to energy consumption in Case 2. A direct comparison of the net expenditures in Cases 1 and 2 shows that if $\lambda_b > c_s + f + \lambda_s$, the hybrid-prosumer should buy a battery to minimize expenditure, keeping other factors constant. Otherwise, if $\lambda_b < c_s + f + \lambda_s$, the household should not buy a battery as it costs more than buying electricity from the grid.

3.2. Net Consumption with and without Energy Storage

If $E_G < E_c$, there is net excess consumption of energy. We first consider the case where the hybrid-prosumer owns an energy storage system with its HES (Case 3) and then present the case where there is no energy storage (Case 4).

3.2.1. Case 3: With Energy Storage

With a battery, the hybrid-prosumer can consume all its generated energy. In this case, a ranges from zero to the maximum feasible amount which is equal to E_G/E_c. aE_c is the fraction of energy consumption satisfied from instant generation (matched generation), therefore $(1-a)E_c$ is the consumption satisfied from the battery ($E_G - aE_c$), while any remaining consumption need is fulfilled by the grid ($E_c - E_G$).

The household's electricity bill is calculated as $(E_c - E_G)\lambda_b$. This household does not have excess energy to send to the grid. The household's net expenditure is $(E_c - E_G)\lambda_b + \sum c_g E_g + (E_G - aE_c)(c_s + f) + \beta^2/2$. As in Case 1, we set up the Lagrangian function in order to find optimal solutions. The first order conditions are

$$\begin{aligned}
\frac{\partial L(.)}{\partial \beta} &= \beta - \eta E_c = 0 \\
\frac{\partial L(.)}{\partial E_c} &= \lambda_b - a(c_s + f) - \eta\beta = 0 \\
\frac{\partial L(.)}{\partial \eta} &= E_u - \beta E_c = 0 \\
\frac{\partial L(.)}{\partial E_1} &= -\lambda_b + c_1 + c_s + f = 0 \\
&. \\
&. \\
&. \\
\frac{\partial L(.)}{\partial E_g} &= -\lambda_b + c_g + c_s + f = 0
\end{aligned} \tag{8}$$

Using the first order conditions in Equation (8), one can derive the conditional demand functions for β, E_c, and E_g. Solutions for E_g are found at the point where the average costs of production from all sources are equalized, and $\lambda_b = c_g + c_s + f$ holds. The household produces energy up to the point where the marginal cost of using the HES (generation and storage) is equal to the marginal benefit of using the HES (avoiding the purchase of electricity at the retail price).

We find $P_{EC,3} = \lambda_b - a(c_s + f)$, therefore the unit price of energy consumption is equal to the retail price of electricity less the unit cost of energy passing through the battery, for the fraction of energy that is stored in the battery. When the household uses energy stored in its battery, it avoids paying the full retail price of electricity. Closed form solutions are identical to Equations (4)–(6), with $P_{EC,3}$ instead of $P_{EC,1}$.

3.2.2. Case 4: Without Energy Storage

This case is similar to Case 3, with the exception that the hybrid-prosumer does not own batteries. The household has to satisfy some of its consumption from the grid. The electricity bill is $(1-a)E_c\lambda_b$, and the amount of energy send back to the grid is $E_G - aE_c$. Net expenditure is calculated as $\sum c_g E_g + \lambda_b(1-a)E_c - (E_G - aE_c)\lambda_s + \beta^2/2$. The first order conditions of the Lagrangian functions are identical to those presented in Case 2.

The effective per unit price of energy consumption, $P_{EC,4} = P_{EC,2} = \lambda_b(1-a) + a\lambda_s$, is the same as in Case 2. If $f + c_s + \lambda_s > \lambda_b$, then $P_{EC,2} > P_{EC,3}$, which implies that energy consumption in Case 4 is lower than energy consumption in Case 3. Given that households are net consumers of energy, the household with no battery has a lower optimal energy consumption than the household with a battery.

A direct comparison of the net expenditures in Cases 3 and 4 shows that it is cheaper to install the HES without a battery if $f + c_s + \lambda_s > \lambda_b$ holds. Thus, we find that whether the household is a net generator or a net consumer of energy, it should not buy a battery if $f + c_s + \lambda_s > \lambda_b$. In addition, we find that the effective per unit price of energy consumption is the same for a net generator and a net consumer as long as the system does not have a battery.

3.3. Net Zero House with and without Energy Storage

In this sub-section, we consider a net zero house, where $E_G = E_c$. In this case, the decision of how much to produce relative to consumption is no more relevant, as the energy production is exactly equal to the consumption. The household minimizes net expenditure subject to the net zero $(E_c = E_G)$ and efficiency constraints $(E_u = \beta E_c)$. First, we consider a hybrid-prosumer with a battery (Case 5), and next we consider a household with no battery (Case 6).

3.3.1. Case 5: Net Zero House with Battery

The hybrid-prosumer instantly consumes aE_c, and derives the rest of its consumption from the battery. The household does not need to buy energy from the grid and does not have excess energy to sell back to the grid. The household's net expenditure is given as $\sum c_g E_g + (c_s + f)(1-a)E_c + \beta^2/2$. The first order conditions from the Lagrangian equation are

$$
\begin{aligned}
&L(\beta, E_g, \eta) = \sum c_g E_g + (c_s + f)(1-a)E_G + \beta^2/2 + \eta(E_u - \beta E_G) \\
&\frac{\partial L(.)}{\partial \beta} = \beta - \eta E_G = 0 \\
&\frac{\partial L(.)}{\partial E_1} = c_1 + (c_s + f)(1-a) - \eta\beta = 0 \\
&. \\
&. \\
&. \\
&\frac{\partial L(.)}{\partial E_g} = c_g + (c_s + f)(1-a) - \eta\beta = 0 \\
&\frac{\partial L(.)}{\partial \eta} = E_u - \beta E_G = 0
\end{aligned}
\tag{9}
$$

The household produces and consumes energy up to the point where the average costs of production from the different energy sources are equalized. We find that $P_{EC,5} = c_g + (c_s + f)(1-a)$ and the effective per unit price of energy consumption is the cost of using the battery for the fraction of energy consumption that comes from charging and discharging the battery, and the average cost of producing energy. Equations (4)–(6) are re-written with this adjustment.

3.3.2. Case 6: Net Zero House without Battery

The hybrid-prosumer instantly consumes aE_c, while the rest is bought from the grid. Without battery, the household's excess energy is sent back to the grid. Hence, the household's net expenditure is $\sum c_g E_g + \lambda_b(1-a)E_c - \lambda_s(1-a)E_G + \beta^2/2$. We solve for $P_{EC,6} = (\lambda_b - \lambda_s)(1-a) + c_g$. The effective per unit price of energy consumption is the fraction of energy purchased from the grid, less the compensation earned from selling energy back to the grid, plus the average cost of onsite energy production. In Cases 5 and 6, the buy-back rate is not necessarily equalized to the average cost of energy production onsite.

Comparing the net expenditures in Cases 5 and 6, we find that the household should not buy a battery if the average cost of buying, installing, and using the battery exceeds the difference between the retail price of energy and the buy-back rate, $f + c_s > \lambda_b - \lambda_s$. Furthermore, with $c_s + f > \lambda_b - \lambda_s$ we find that $P_{EC,5} > P_{EC,6}$, which implies that the net zero house with a battery has a lower energy consumption compared to the net zero house with no batteries.

If $f + c_s < \lambda_b - \lambda_s$, then the household should buy a battery because average battery costs are lower.

If $f + c_s = \lambda_b - \lambda_s$ then the net zero household is indifferent between buying and not buying the battery.

4. Discussion

The model presented in the previous section illustrates that P_{EC} differs for different types of hybrid-prosumers as detailed by the six cases we considered. Except for $P_{EC,2} = P_{EC,4}$, the other cases have different effective price of energy consumption. Differences in P_{EC} across hybrid-prosumers has implications on the optimal demand for energy consumption and energy services. Specifically, a hybrid-prosumer with a higher P_{EC} has a lower demand for energy consumption, a lower demand for energy services and a higher shadow price of energy services (see Equation (6)). P_{EC} does not affect the optimal level of efficiency rating (β), which only depends on the hybrid-prosumer's income level [47].

In all six cases, the effective per unit price of energy consumption for a hybrid-prosumer depends on the percentage of matched-generation, a, which in turn depends directly on the number of renewable energy sources (G). Since having multiple energy sources is expected to increase matched generation, there is a positive relationship between G and a. The rate of change in P_{EC} with respect to a change in a is non-positive for all cases. An increase in matched-generation (due to an increase in G, for instance) reduces the effective per unit price of energy consumption, making energy consumption relatively cheaper. The exact magnitude of the change in P_{EC} with respect to a, depends on whether the household owns a battery $(-f - c_s < 0)$ or not $(\lambda_s - \lambda_b \leq 0)$.

As Table 2 illustrates the rate of change in energy consumption with respect to a is non-negative for all the six cases. This is because an increase in a makes energy consumption relatively cheaper. This implies that, as the number of renewable energy sources, G, increases, demand for energy consumption and demand for energy services also increase irrespective of the ownership of energy storage. For example, a PV–wind–hydro prosumer ($G = 3$) would consume more energy compared to a PV–wind prosumer ($G = 2$), keeping other factors constant. This suggests a "generation rebound effect", whereby hybrid-prosumers with more energy generating sources have higher overall energy consumption compared to hybrid-prosumers with fewer energy generating sources. This result is consistent with McAllister [41] who shows that PV adopters in California increase their energy consumption post-PV because PV reduced the marginal cost of energy.

Table 2. Comparing the six cases.

Cases	Effective per Unit Price of Energy Consumption (P_{EC})	$\frac{\partial E_c}{\partial a}$
Net generator with battery	$(f + c_s)(1 - a) + \lambda_s$	$\frac{(f+c_s)(I/1.5)}{[(f+c_s)(1-a)+\lambda_s]^2}$
Net generator without battery	$a\lambda_s + (1 - a)\lambda_b$	$\frac{(\lambda_b-\lambda_s)(I/1.5)}{[a\lambda_s+(1-a)\lambda_b]^2}$
Net consumer with battery	$\lambda_b - a(c_s + f)$	$\frac{(f+c_s)(I/1.5)}{[\lambda_b-a(c_s+f)]^2}$
Net consumer without battery	$a\lambda_s + (1 - a)\lambda_b$	$\frac{(\lambda_b-\lambda_s)(I/1.5)}{[a\lambda_s+(1-a)\lambda_b]^2}$
Net zero with battery	$(c_s + f)(1 - a) + c_g$	$\frac{(I/1.5)(c_s+f)}{[(c_s+f)(1-a)+c_g]^2}$
Net zero without battery	$(\lambda_b - \lambda_s)(1 - a) + c_g$	$\frac{(I/1.5)(\lambda_b-\lambda_s)}{[(\lambda_b-\lambda_s)(1-a)+c_g]^2}$

In the remainder of this section, we outline how the model can be applied to guide a hybrid-prosumer's decision-making in the US residential sector. Coughlin and Cory [54] show that the retail price of electricity plays a major role in the decision to install PV in the residential sector. Likewise, Borenstein [55] shows that the electricity price structure in California has contributed to the increase in the private value of renewable energy generated by prosumers. We consider the 2017 US average retail electric rate of 12.88 cents per kWh and the average wholesale price of 3.36 cents per kWh. We illustrate how these rates affect a hybrid-prosumer's decision-making process based on the framework presented in Section 3. We consider the case where the buy-back rate is equal to the wholesale rate. That is, $\lambda_b = 12.88$, $\lambda_s = 3.36$ and $\lambda_b - \lambda_s = 9.52$ cents per kWh.

According to Ardani et al. [56], estimation and comparison of the cost of energy storage for residential systems is not easy because of the diversity of storage applications. Storage costs are estimated based on the amount of energy stored (energy capacity in kWh), or based on its power rating (the rate at which it charges or discharges in kW). Ardani et al. [56] survey the literature and summarize per kWh storage costs. Most of the studies focus on hardware costs, while only a few look at the non-hardware cost of batteries. Based on the values presented by Ardani et al. [56], we use an average cost of $500 per kWh. This value is close to the cost estimate we obtained from our own research by talking to vendors. For example, EnergySage Inc., an online marketplace for renewable energy estimates the price of energy storage to be between $400 and $750 per kWh [57]. This covers the cost of material, inverter, and installation. Quotes from NEC Energy Solutions, an energy storage manufacturer, indicate that the price of an energy storage equipment is between $600 and $800 per kWh.

Based on a study by the Energy Information Administration [58], the US average levelized cost of energy production from renewable sources—such as wind, solar, hydro, solar thermal, and biomass—is $0.1058 per kWh after considering tax credits. Following this information, we assume that $c_g = 10.58$ cents per kWh and it results that $c_g > \lambda_s$. Given current market conditions, it is reasonable to conclude that the per unit price of energy storage is significantly higher than the retail price of electricity. This implies that the net expenditure of a hybrid-prosumer is higher with battery compared to the no battery cases. Thus, Cases 1, 3, and 5 are currently high cost options and the household should not buy a storage component. Therefore, the decision-making process is reduced to determining how much energy to produce relative to energy consumption. We present the net expenditures of these remaining options at equilibrium

Case 2 (net generator): $E_c P_{EC,2} + \beta^2/2$ where $P_{EC,2} = a\lambda_s + (1-a)\lambda_b$

Case 4 (net consumer): $E_c P_{EC,2} + \beta^2/2$ where $P_{EC,4} = a\lambda_s + (1-a)\lambda_b$

Case 6 (net zero house): $E_c P_{EC,6} + \beta^2/2$ where $P_{EC,6} = (\lambda_b - \lambda_s)(1-a) + c_g$

From the economic point of view, it does not matter whether the hybrid-prosumer is a net generator or a net consumer, it will end up experiencing the same effective per unit price of energy and shadow prices for energy services. That is, net generators do not necessarily have higher demand for energy consumption compared to net consumers. This result is in contrast to the findings of McAllister [41] who finds that households in California with oversized PV (large PV relative to consumption) tend to have higher energy consumption, as they are more likely to have energy-intensive plans, such as home expansion or improvement.

Since the buy-back price of energy is less than the average cost of generating energy from the renewable source, $\lambda_s < c_g$, it follows that $P_{EC,2} < P_{EC,6}$, which implies that energy consumption in Case 6 (net zero house) is lower than both Case 2 (net generator) and 4 (net consumer), for all values of a.

5. Conclusions

Why do residential units adopt a hybrid instead of a single renewable energy system? The economic model presented in this study illustrates how the production of renewable energy from multiple sources affects energy efficiency, energy services, and energy consumption choices in the residential sector. It is a more insightful look into the household's decision-making process that complements a benefit–cost analysis approach.

We find that a hybrid system increases the percentage of energy consumption derived from onsite energy generation, which in turn reduces the effective price of energy consumption. With a lower price of energy consumption, hybrid-prosumers use more electricity. Furthermore, hybrid-prosumers also increase their consumption of energy services, which is the source of consumer utility.

The economic principles derived in this study suggest that the current price of energy storage is not competitive enough for hybrid-prosumers to pursue it. The conditions derived in Section 4 show how low the price of energy storage should be for a hybrid-prosumer to consider owning a battery. Suppose these conditions are met, such that the average cost of storage (battery installation and degradation) is less than the difference between the energy price bought from the grid and the buy-back rate ($f + c_s < \lambda_b - \lambda_s$). This allows the hybrid-prosumer to rely less on the grid, and meet objectives related to reducing environmental impact. More studies are needed to examine the feasibility of including different types of energy storage systems in a residential HES.

The model can also be extended to further capture any utility gains from greenhouse gas emission reductions. For example, Sun et al. [1] suggest that in addition to minimizing net expenditures, prosumers may have additional objectives, such as reducing the environmental impact of their energy usage. The utility function presented in Equation (1) offers a flexible framework for describing behavior and it can be modified as in Sun et al. [1] by adding the prosumer's preference for renewable energy sources.

This study can also be extended by validating some of the model predictions using data from hybrid-prosumers (e.g., data from a survey of the residential sector). The dataset should be rich enough to capture observable and measurable variables, such as energy consumption, as well as behavioral parameters, such as the attitude of residents towards energy use.

Finally, we wish to acknowledge some of the limitations of the model. The model presented in this study is a static model, with no temporal and spatial dimensions. Furthermore, we have not delved into the impact that policies and regulations could have on hybrid-prosumers. Regulatory standards governing electric rate structures and compensation mechanisms are expected to influence the choices available to hybrid-prosumers. Also, tax incentives and credits are likely critical in the adoption of renewable energy in the residential sector. Studies are needed to understand what types of regulations and incentives, if any, provide the proper motivation for prosumers to make economically optimal decisions.

Author Contributions: All Authors contributed to the paper as follows: conceptualization, J.D.S.; formal analysis, M.G.F., G.G., A.-M.I.; investigations, J.D.S.; review of the literature A.-M.I.; writing—original draft preparation, M.G.F., G.G.; writing—review and editing, M.G.F., G.G., A.-M.I. and J.D.S.

Funding: This research received no external funding.

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

References

1. Sun, Q.; Beach, A.; Cotterell, M.E.; Wu, Z.; Grijalva, S. An economic model for distributed energy prosumers. In Proceedings of the 46th Hawaii International Conference on System Sciences, Wailea, HI, USA, 7–10 January 2013; pp. 2103–2112.
2. MacGill, I.; Smith, R. Consumers or prosumers, customers or competitors? Some Australian perspectives on possible energy users of the future. *Econ. Energy Environ. Policy* **2017**, *6*, 51–70. [CrossRef]
3. Green, R.; Staffell, I. "Prosumage" and the British electricity market. *Econ. Energy Environ. Policy* **2017**, *6*, 33–50. [CrossRef]
4. Schill, W.-P.; Zerrahn, A.; Kunz, F. Prosumage of solar electricity: Pros, cons and the system perspective. *Econ. Energy Environ. Policy* **2017**, *6*, 7–32. [CrossRef]
5. Zarte, M.; Pechmann, A. Economic analysis of renewable energy production with photovoltaic and solar thermal systems for small and medium sized enterprises. In Proceedings of the EuroSun 2016. International Solar Energy Society, Palma de Mallorca, Spain, 11–14 October 2016.
6. Jung, J.; Tyner, W.E. Economic and Policy analysis for solar PV systems in Indiana. *Energy Policy* **2014**, *74*, 123–133. [CrossRef]
7. Swift, K.D. A comparison of the cost and financial returns for solar photovoltaic systems installed by businesses in different locations across the United States. *Renew. Energy* **2013**, *57*, 137–143. [CrossRef]
8. Ghaitha, A.F.; Epplina, F.M.; Frazierb, R.S. Economics of household wind turbine grid-tied systems for five wind resource levels and alternative grid pricing rates. *Renew. Energy* **2017**, *109*, 155–167. [CrossRef]
9. Ghaitha, A.F.; Epplina, F.M.; Frazierb, R.S. Economics of grid-tied household solar panel systems versus grid-only electricity. *Renew. Sustain. Energy Rev.* **2017**, *76*, 407–424. [CrossRef]

10. Tervo, E.; Agbim, K.; DeAngelis, F.; Hernandez, J.; Kim, H.K.; Odukomaiyaa, A. An economic analysis of residential photovoltaic systems with lithium ion battery storage in the United States. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1057–1066. [CrossRef]
11. Khan, M.J.; Iqbal, M.T. Pre-feasibility Study of Stand-Alone Hybrid Energy systems for applications in Newfoundland. *Renew. Energy* **2005**, *30*, 835–854. [CrossRef]
12. QVARTZ. Emergence of Hybrid Renewable Energy Systems. 2019. Available online: https://qvartz.com/media/2019/hybrid_renewableenergy.pdf (accessed on 9 July 2019).
13. US Department of Energy. Hybrid Wind and Solar Electric Systems. Available online: https://energy.gov/energysaver/hybrid-wind-and-solar-electric-systems (accessed on 9 July 2019).
14. US Department of Energy. Off-Grid or Stand-Alone Renewable Energy Systems. Available online: https://energy.gov/energysaver/grid-or-stand-alone-renewable-energy-systems (accessed on 9 July 2019).
15. Couture, T.; Barbose, G.; Jacobs, D.; Parkinson, G.; Chessin, E.; Belden, A.; Wilson, H.; Barrett, H.; Rickerson, W. *Residential prosumers: drivers and policy options (re-prosumers)*; Meister Consultants Group; Lawrence Berkeley National Lab. (LBNL): Berkeley, CA, USA, 2014.
16. Ginn, C. Energy Pick n' Mix: Are Hybrid Systems the Next Big Thing? 2016. Available online: https://blog.csiro.au/energy-pick-n-mix-hybrid-systems-next-big-thing/ (accessed on 9 July 2019).
17. Center for Sustainable Systems. U.S. Renewable Energy Factsheet 2018, Pub. No. CSS03-12. University of Michigan. Available online: http://css.umich.edu/sites/default/files/U.S._Renewable_Energy_Factsheet_CSS03-12_e2018.pdf (accessed on 9 July 2019).
18. Shove, E. Gaps, Barriers and Conceptual Chasms: Theories of Technology Transfer and Energy in Buildings. *Energy Policy* **1998**, *26*, 1105–1112. [CrossRef]
19. Jaffe, A.B.; Stavins, R.N. The energy efficiency gap: What does it mean? *Energy Policy* **1994**, *22*, 804–810. [CrossRef]
20. Soysal, O.A.; Soysal, H.S. A residential example of hybrid wind-solar energy system: WISE. In Proceedings of the Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008; pp. 1–5.
21. Yang, N.C.; Tseng, W.C. Impact assessment of a hybrid energy-generation system on a residential distribution system in Taiwan. *Energy Build.* **2015**, *91*, 170–179. [CrossRef]
22. Cetin, E.; Yilanci, A.; Oner, Y.; Colak, M.; Kasikci, I.; Ozturk, H.K. Electrical analysis of a hybrid photovoltaic-hydrogen/fuel cell energy system in Denizli, Turkey. *Energy Build.* **2009**, *41*, 975–981. [CrossRef]
23. Markham, D. Hybrid Rooftop Wind and Solar Generator Now Available in U.S. for Early Adopters. 2015. Available online: https://www.treehugger.com/wind-technology/hybrid-rooftop-wind-and-solar-generator-now-available-us-early-adopters.html (accessed on 9 July 2019).
24. General Electric Renewable Energy Website. More Than Just a Trend. Available online: https://www.gerenewableenergy.com/hybrid (accessed on 9 July 2019).
25. Gupta, A.; Bais, A.S. Hybrid Solar Wind Market Size By Product (Standalone, Grid connected), End Use (Residential, Commercial, Industrial), Industry Analysis Report, Regional Outlook (U.S., Canada, U.K, Germany, China, India, Australia, Japan, South Africa, Nigeria, Tanzania, Chile, Brazil), Application Potential, Price Trends, Competitive Market Share & Forecast, 2016–2024, Report ID: GMI830. Available online: https://www.gminsights.com/industry-analysis/hybrid-solar-wind-market (accessed on 9 July 2019).
26. Deshmukh, M.K.; Deshmukh, S.S. Modeling of hybrid renewable energy systems. *Renew. Sustain. Energy Rev.* **2008**, *12*, 235–249. [CrossRef]
27. Gupta, A.; Saini, R.P.; Sharma, M.P. Modelling of hybrid energy system—Part I: Problem formulation and model development. *Renew. Energy* **2011**, *36*, 459–465. [CrossRef]
28. Gupta, A.; Saini, R.P.; Sharma, M.P. Modelling of hybrid energy system—Part III: Case study with simulation results. *Renew. Energy* **2011**, *36*, 474–481. [CrossRef]
29. Li, C.; Ge, X.; Zheng, Y.; Xu, C.; Ren, Y.; Song, C.; Yang, C. Techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi, China. *Energy* **2013**, *55*, 263–272. [CrossRef]
30. Ashok, S. Optimised model for community-based hybrid energy system. *Renew. Energy* **2007**, *32*, 1155–1164. [CrossRef]

31. Shaahid, S.M.; Elhadidy, M.A. Technical and economic assessment of grid-independent hybrid photovoltaic–diesel–battery power systems for commercial loads in desert environments. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1794–1810. [CrossRef]
32. Shaahid, S.M.; Elhadidy, M.A. Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—A step to clean future. *Renew. Sustain. Energy Rev.* **2008**, *12*, 488–503. [CrossRef]
33. Shaahid, S.M.; El-Amin, I. Techno-economic evaluation of off-grid hybrid photovoltaic-diesel-battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development. *Renew. Sustain. Energy Rev.* **2009**, *13*, 625–633. [CrossRef]
34. Lv, Z.; Wang, Z.; Xu, W. A Techno-Economic Study of 100% Renewable Energy for a Residential Household in China. *Energies* **2019**, *12*, 2109. [CrossRef]
35. Diaf, S.; Belhamel, M.; Haddadi, M.; Louche, A. Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica Island. *Energy Policy* **2008**, *36*, 743–754. [CrossRef]
36. Ani, V.A. Design of a Reliable Hybrid (PV/Diesel) Power System with Energy Storage in Batteries for Remote Residential Home. *J. Energy* **2016**. [CrossRef]
37. Syed, A.M.; Fung, A.S.; Ugursal, V.I.; Taherian, H. Analysis of PV/wind potential in the Canadian residential sector through high-resolution building energy simulation. *Int. J. Energy Res.* **2009**, *33*, 342–357. [CrossRef]
38. Bazilian, M.; Onyeji, I.; Liebreich, M.; MacGill, I.; Chase, J.; Shah, J.; Gielen, D.; Arent, D.; Landfear, D.; Zheng, S. Re-considering the economics of photovoltaic power. *Renew. Energy* **2013**, *53*, 329–338. [CrossRef]
39. Nadel, S. Solar and Energy Efficiency Need to Work Together Like Peanut Butter and Jelly. 2016. Available online: http://aceee.org/blog/2016/09/solar-and-energy-efficiency-need-work (accessed on 9 July 2019).
40. Langheim, R.; Arreola, G.; Reese, C. Efficiency Motivations and Actions of California Solar Homeowners, 2014 ACEEE Summer Study on Energy Efficiency in Buildings. Available online: https://aceee.org/files/proceedings/2014/data/papers/7-1156.pdf (accessed on 9 July 2019).
41. McAllister, J.A. Solar Adoption and Energy Consumption in the Residential Sector. UC Berkeley Electronic Thesis and Dissertation, 2012. Available online: http://digitalassets.lib.berkeley.edu/etd/ucb/text/McAllister_berkeley_0028E_12779.pdf (accessed on 9 July 2019).
42. Fell, M.J. Energy Services: A Conceptual Review. *Energy Res. Soc. Sci.* **2017**, *27*, 129–140. [CrossRef]
43. Guertin, C.; Kumbhakar, S.C.; Duraiappah, A.K. *Determining Demand for Energy Services: Investigating Income-Driven Behaviors*; International Institute for Sustainable Development: Winnipeg, MB, Canada, 2003.
44. Hunt, L.C.; Ryan, D.L. *Economic Modelling of Energy Services: Rectifying Mis-Specified Energy Demand Functions*; Surrey Energy Economics Center: Surrey, UK, 2014.
45. Grepperud, S.; Rasmussen, I. A general equilibrium assessment of rebound effects. *Energy Econ.* **2004**, *26*, 261–282. [CrossRef]
46. Freire-González, J. Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households. *Ecol. Model.* **2011**, *223*, 22–40. [CrossRef]
47. Fikru, M.G.; Gelles, G.; Ichim, A.M.; Kimball, J.W.; Smith, J.D.; Zawodniok, M.J. An economic model for residential energy consumption, generation, storage and reliance on cleaner energy. *Renew. Energy* **2018**, *119*, 429–438. [CrossRef]
48. Wilson, C.; Dowlatabadi, H. Models of Decision Making and Residential Energy Use. *Annu. Rev. Environ. Resour.* **2007**, *32*, 169–203. [CrossRef]
49. Stern, P.C. Contributions of Psychology to Limiting Climate Change. *Am. Psychol.* **2011**, *66*, 303–314. [CrossRef] [PubMed]
50. Sanstad, A.H. Notes on the Economics of Household Energy Consumption and Technology Choice. Available online: https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/consumer_ee_theory.pdf (accessed on 9 July 2019).
51. Jansson, P.M. Net Metering PV Distributed Resources Benefits All Stakeholders on PJM. In Proceedings of the America Solar Energy Society National Solar Conference, San Francisco, CA, USA, 10–13 July 2016.
52. Solar Power World Website. What is the Best Type of Battery for Solar Storage? Updated May 2018. Available online: https://www.solarpowerworldonline.com/2015/08/what-is-the-best-type-of-battery-for-solar-storage/ (accessed on 9 July 2019).

53. Every, J.; Li, L.; Dorrell, D.G. Optimal selection of small-scale hybrid PV-battery systems to maximize economic benefit based on temporal load data. In Proceedings of the 2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA), Siem Reap, Cambodia, 18–20 June 2017; pp. 471–476.
54. Coughlin, J.; Cory, K. *Solar Photovoltaic Financing: Residential Sector Deployment (NREL/TP-6A2-44853)*; National Renewable Energy Laboratory: Golden, CO, USA, 2009.
55. Borenstein, S. Private Net Benefits of Residential Solar PV: The Role of Electricity Tariffs, Tax Incentives, and Rebates. *J. Assoc. Environ. Resour. Econ.* **2017**, *4*, 85–122. [CrossRef]
56. Ardani, K.; O'Shaughnessy, E.; Fu, R.; McClurg, C.; Huneycutt, J.; Margolis, R. *Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016 (No. NREL/TP-7A40-67474)*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2016.
57. Energy Sage Website. How Much Does Solar Storage Cost? Understanding Solar Battery Prices. Available online: https://www.energysage.com/solar/solar-energy-storage/what-do-solar-batteries-cost/ (accessed on 9 July 2019).
58. Energy Information Administration. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017. Independent Statistics and Analysis*; United States Energy Information Administration: Washington, DC, USA, 2017.