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Energy for off-grid homes: Reducing costs through joint hybrid system and energy efficiency optimization

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ABSTRACT

This paper develops a new process for identifying the lowest cost package of energy efficiency measures (EEM) and hybrid energy system configuration for off-grid homes. Hybrid energy systems, which combine two or more types of energy technologies, often require significant capital expenditure, however, the cost can be reduced by applying EEM to the house to decrease energy demand. The method proposed here, termed Combined Optimization Process (COP), was tested on an off-grid hypothetical case and incorporates an iterative assessment of a building energy and efficiency optimization tool (BEopt) and a hybrid system optimization tool (HOMER). The COP results were compared with the base case where no efficiency measures were applied, and also with a standard process, which involved a selection of best-practice efficiency measures. The COP method yielded net present cost savings of 10% less than the base case, and 5% less than the standard process. The COP method developed in this paper is applicable for existing houses converting to off-grid status as well as for the design stage of off-grid houses.

1. Introduction

Off-grid houses using hybrid systems often incorporate renewable energy technologies, such as photovoltaic (PV) panels, wind turbines, micro-hydro generators, as well as traditional technologies such as batteries and fossil-fuel generators. Although hybrid systems typically have lower operating and maintenance costs compared to a single technology system (i.e. a diesel generator), they often require significant capital expenditure. The cost is influenced by the choice of technology component mix and the overall size of the system. In addition, EEM that lower energy demand will reduce the cost of the hybrid system.

A key objective in off-grid homes is determining the most cost-efficient way of delivering all the energy services required. This has two broad dimensions. Selecting the least cost (capital and operational) energy demand technology mix (for example energy-efficient appliances as well as other technologies that reduce energy demand such as high levels of insulation). Secondly, selecting the least cost (capital and operational) energy supply technologies (for example the type and quantity for PV panels). In the literature, there is much in a way of optimization tools for energy supply and also optimization tools for energy demand. The following two sections examine the literature and the range of optimization tools used in these two broad dimensions.

1.1. Hybrid system optimization

Given the wide variety and high cost of technologies available, optimization software is commonly used to identify the least cost system for a specific application. This literature review examines a number of studies that utilize optimization tools, followed by a review of the literature comparing and contrasting the capabilities of the key software packages commonly used.

Optimization software packages are used for a range of reasons; from determining the design of the least-cost system to examining the impact of introducing new technologies on the operational cost of an existing system. For example, Rashid et al. [1] investigate with the use of HOMER (Hybrid Optimization Model for Electric Renewable) a PV-wind-diesel energy system for enhanced energy demand at coastal areas in Bangladesh, comparing and contrasting the optimal solutions in different locations. A recent study utilized HOMER to determine the optimal hybrid system for the island village Fenfushi, Maldives. It explores the aspect of load differentiation by importance, and models loads of low importance as a deferrable load within HOMER which resulted in the lower-cost hybrid system [2]. Hossain et al. [3] examined a tourist resort that

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Table 1
Comparison of energy supply simulation tools (adapted from [8]).

	SAM	CREST	PVWATTS	windPro	Reopt	HOMER	EnergyPLAN	KomMod	TRYNSIS	Energy+
Simulation	x	x	x	x	x	x	x	x	x	x
Optimization					x	x				
Photovoltaics	x	x	x		x	x	x	x	x	x
Wind Energy	x	x		x	x	x	x	x	x	x
Battery Storage	x				x	x	x	x	x	x
Residential modeling	x	x	x						x	x
Finance	x	x	x	x	x	x	x	x		
Performance	x			x	x	x	x	x	x	x
Free of charge	x	x	x				x	x		x

was completely dependent on diesel generation and examined the theoretical cost savings through the use of PV batteries and wind utilizing the HOMER tool for simulation and results. Similarly, Halabi and Mekhilef [4] searched for the optimal hybrid system to supply electricity to an entire remote village in Malaysia. Again, HOMER was used to determine the optimal system which in this case consisted of the PV, diesel and battery components.

There are a number of different software and simulation tools assisting the design and optimization of hybrid systems. These tools attracted noticeable scholarly attention about a decade ago and a few studies can serve as examples. Sinha and Chandel [5] analyzed and classified different software design and simulation tools for hybrid systems according to their capability, availability, features, and applications. Similar studies have been carried out earlier by Bernal-Agustín and co-authors [6,7], and more recently Tozzi and Jo [8] who provided an overview of different energy supply simulation tools against criteria listed in Table 1. Overall, HOMER appears repeatedly and consistently as a selected tool for cost optimization studies.

1.2. Building energy optimization

Montana and Sanseverino [9] reviewed 64 studies on achieving low energy buildings that were mainly focused on optimization tools used to determine the low energy building configuration. In response to the European directive requiring new buildings to meet low energy requirement standards, a number of studies model scenarios to achieve high energy building performance sourced predominantly by a low amount of renewable energy. For example, D'Agostino and Parker [10] develop a simulation-based optimization framework for cost-optimal choices and EEM for new buildings and applied it to 16 residential building prototype with respect to hourly climatic data, various construction methods, cost data, and energy consumption. With the use of optimization software EnergyPlus, the authors demonstrate energy savings of 90% compared to the base case with climate representing the strongest variable in yielded results. There are numerous studies that examine the effects of implementing one or more energy-saving measures yet just a few studies try to ascertain the best total value solution. While optimizing grid-tied houses with hybrid systems is a well-researched area, there is little literature on the application of EEM in the off-grid scenario. Most of the studies that consider off-grid settings look into injustice in energy provision of grid-tied houses vs off-grid houses and focus on improvements in national energy policies [11,12]. Yet, to our knowledge, there is no recent literature that covers retrofitting and optimization of existing houses set in rural off-grid conditions and hence can inform rural homeowners on cost-effective renovation measures leading to least energy load on the house. Closest to this in the grid-tied scenario is a recent study of [13] who evaluated retrofitting investments necessary to reach passive energy status and was based on two Swedish houses from 1960 to 1970. Alamri and Iqbal [14] conducted a study in which EEM were chosen on best practices (and the resulting energy demand of the building was simulated and produced by using BEopt) then the optimal hybrid system was determined (in this case using HOMER). Alemi and Loge [15] constructed in BEopt a hypothetical net-zero affordable house.

Methods that estimate the optimal mix of efficiency measures and energy supply technologies for grid-tied houses generally combine simulation and optimization tools. Attia et al. [16] find that the two most mentioned tools that merge simulation and optimization techniques in building performance optimization analysis are BEopt[1] (for residential buildings) and Opt-E-Plus[2] (for commercial buildings), both developed by the National Renewable Energy Laboratory. BEopt^{TM} (Building Energy Optimization Tool) is a software using a sequential search optimization technique in order to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy. Given that this software is mostly used for grid-tied houses that have the opportunity to buy electricity from the grid, most studies consider solar PV panels as the only available energy generation technology. An off-grid house must generate all the energy required, and should consider all renewable energy sources available in the location, not just solar PV panels. Moreover, other components form a hybrid system, such as batteries, diesel generator, and inverters also need to be taken into account. There is a number of different software packages available to identify an optimal energy load profile. Attia and De Herde [17] carried out a study assessing simulation tools for net-zero energy buildings and Table 2 builds upon their assessment and contrasts 10 available building performance simulation tools against relevant EEM criteria for our study. Despite a range of choices, BeOpt simulation software offers more flexibility in simulations and furthermore, it provides three main interface screens to input criteria used by the simulation software to assess a home's energy profile: the geometry screen, the options screen (insulation levels, window types, etc.), and the site screen (location, weather files, utility rate structures, etc.) [18].

To summarize, our review of existing research has identified several limitations of studies related to the optimization of off-grid housing hybrid systems. These include:

A. Research into energy cost optimization for off-grid houses focuses mostly on energy supply while excluding energy demand, so a global optimal solution is not identified.
B. There is a lack of optimization studies that link energy supply and demand together in order to find an optimal solution to reduce energy demand for residential off-grid houses and thus further reduce hybrid system costs.
C. Existing optimization methods for efficiency measures are designed for grid-tied houses with solar PV, thereby excluding other technologies that are available for off-grid energy systems.

[1] Building Energy Optimization. See http://BEopt.nrel.gov/.
[2] See http://www.nrel.gov/tech_deployment/tools.html.

Table 2
Comparison of building performance simulation tools against EEM criteria (adapted from [17]).

	HEED	eQUEST	Energy10	Vasari	Solar Shoebox	Open Studio	IES VE-Ware	ECOTECT	DesignBuilder	BeOpt
Energy	x	x	x	x	x	x	x	x	x	x
Environmental (CO_2)	x	x	x				x		x	x
Economic	x	x	x						x	x
Envelope Insulation	x	x	x	x	x	x	x	x	x	x
Glazing Performance	x	x	x	x	x		x	x	x	x
Artificial lightning	x	x	x				x		x	x
Mechanical ventilation	x		x						x	x
Cooling system	x	x	x				x		x	x
Heating system	x	x	x				x		x	x
Photovoltaic PV	x		x		x		x			x
Solar Therm. Collectors			x				x			x

In conclusion, most of the studies focus either on the demand or the supply side of optimization and the key contribution of this study is in combining demand with the supply side of HS optimization. Therefore, the objective of this research is to develop a new process that takes into account both efficiency measures and hybrid system components in order to find the optimal combination, resulting in the lowest capital installation and operating cost over the lifetime of the system for an off-grid house.

2. Methods

The approach used for this research is to combine existing hybrid system and energy efficiency simulation tools in order to achieve a complete optimization. We propose an iterative loop process - termed the combined optimization process (COP) - which links a building energy optimization tool that incorporates EEM with a hybrid system optimization tool. This approach only considers the optimal selection of energy production units and EEM. It does not consider the optimal operation of the hybrid system. To test whether the COP delivers the lowest total cost for an off-grid house, we compare the COP results with those from a standard process that applies efficiency measures before optimization of the hybrid system. Both processes were applied to a test case, and net present costs were calculated and compared accordingly.

The total cost to meet the energy requirements of an off-grid house is the total net present cost (NPC_{TOTAL}) and is defined as follows:

$$NPC_{TOTAL} = NPC_{HS} + NPC_{EM} \quad (1)$$

The net present cost of a hybrid system (NPC_{HS}) includes all capital, installation, fuel and maintenance costs over a 20-year lifespan, discounted to the present day. The net present cost of the efficiency measures (NPC_{EM}) is defined similarly.

2.1. Description of standard process

The standard process typically consists of a selection of efficiency measures that are chosen based on best practice, followed by optimization of the hybrid system. Fig. 1 depicts the standard process, consisting of five steps.

Step 1: Assess the building (design, building materials, appliances, etc.) and location (coordinates, weather characteristics), and service levels (required indoor temperature throughout the year, use of appliances etc.), as well as a full

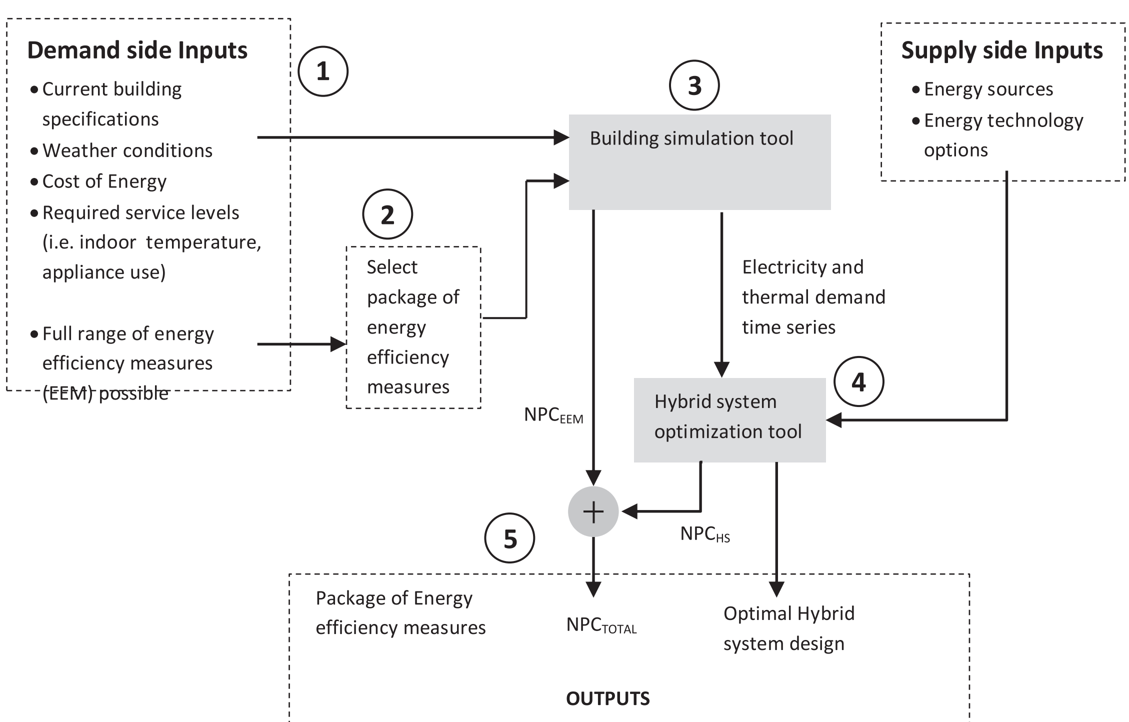

Fig. 1. Process flow of a standard process.

range and cost of EEM that could be applied (e.g., different levels of insulation, types of retrofit double glazing); cost of gas as primary source of energy.

Step 2: Select the appropriate best practice package of efficiency measures, e.g., insulation levels, type of double glazing, etc.

Step 3: Based on the chosen efficiency measures, the modified building characteristics are used in the building energy simulation tool, which calculates the time series energy demand as well as the net present cost of the efficiency measures (NPC_{EM}).

Step 4: The energy demand time series, together with information on available energy sources and technologies, serve as an input into a hybrid system optimization and simulation tool that determines the least cost hybrid system that can provide energy to the house, and the resulting net present cost of the hybrid system (NPC_{HS}).

Step 5: The total net present cost of the system (NPC_{TOTAL}) is simply the sum of the two components, NPC_{HS} and NPC_{EM}.

2.2. Description of the combined optimization process (COP)

The COP consists of a loop that combines building energy optimization tool with a hybrid system optimization tool, the objective being to find a global optimal solution taking into account both energy demand (building elements) and energy supply (hybrid system) variables. This process is described in six steps and presented in Fig. 2.

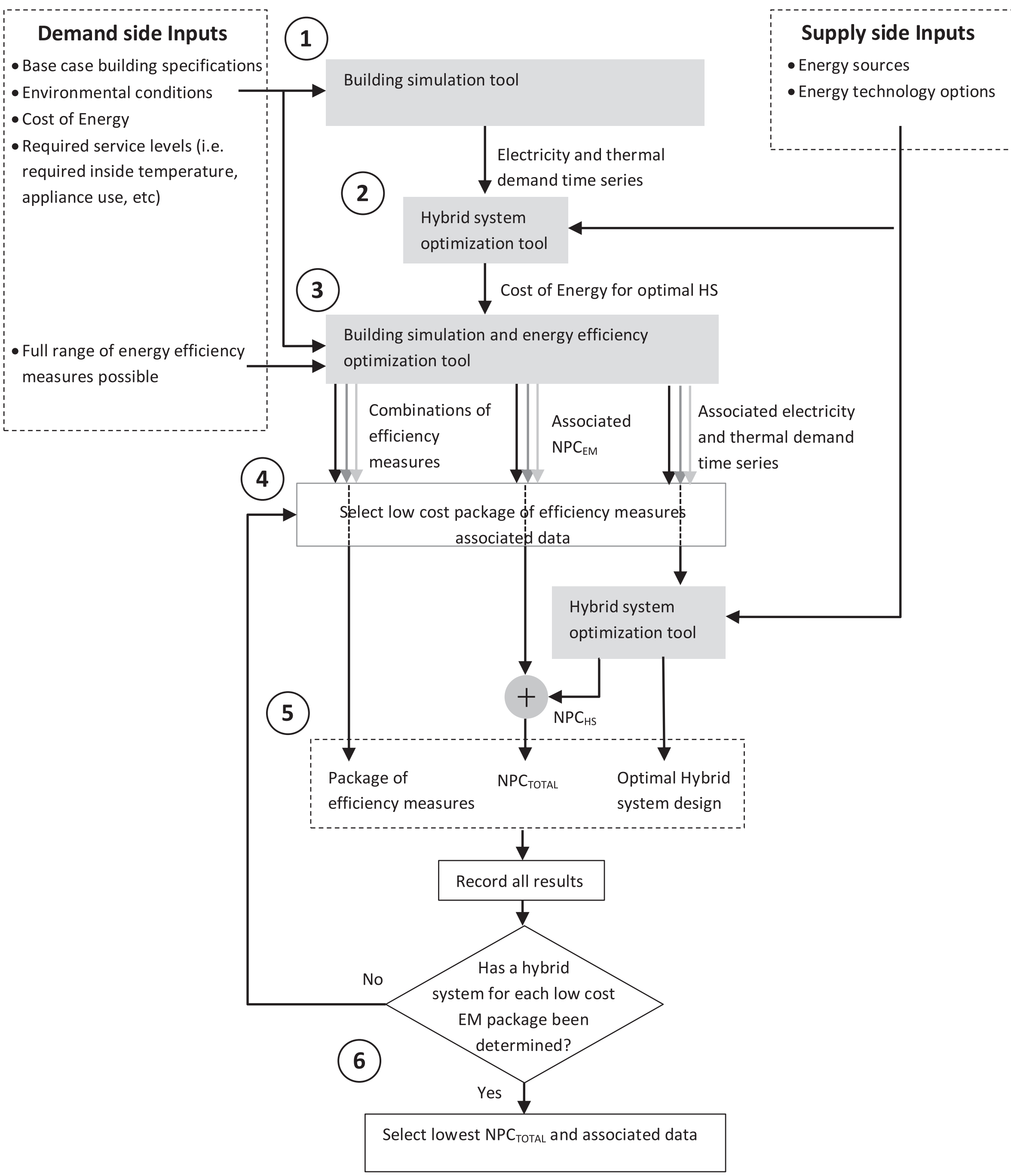

Fig. 2. Process flow of COP.

Step 1: A base case is analyzed, in which the building is simulated in the absence of any efficiency measures (hence NPC_{EEM} is zero), and a time series of energy demand is produced.

Step 2: The energy demand time series and energy sources and technologies available are used as inputs to the hybrid system optimization and simulation tool that determines the least cost hybrid system (NPC_{HS}). From the NPC_{HS}, the cost of energy (average cost per kWh of useful electric energy produced by the system) is calculated.

Step 3: All the possible efficiency measures that can be applied become inputs into the building optimization and simulation tool. More than one option for each appliance/building element is specified (e.g., wall insulation of different *R*-values, different types of glazing, different types of refrigerators). The cost of energy determined in step 2 also becomes an input. The building simulation and energy efficiency tool simulates the building such that each package of efficiency measures are applied. Each time, the electricity demand time series and NPC_{EEM} are produced, as well as a record of which efficiency measure package was applied to the building.

Step 4: The lowest cost result is selected representing the optimal package of efficiency measures, NPC_{EM}, and time series of electricity and thermal demand. Using a hybrid optimization tool, the hybrid system is determined, as is the NPC_{HS} using the time series of electricity demand and energy sources and technologies.

Step 5: The NPC_{HS} is added to the NPC_{EM} to calculate the NPC_{TOTAL} of the system, and all results are recorded (package of efficiency measures and hybrid system).

Step 6: If all efficiency measure packages have not been selected, return to step 5, otherwise, from all the recorded results, select the one with the lowest NPC_{TOTAL}.

In conclusion, the standard process is represented by a single run. It starts with a set of building elements selected on best practice, these parameters are run through a building simulation tool to calculate the demand profile. This demand profile is then used as an input into a hybrid system optimization tool, which provides the least cost hybrid design. Finally, the costs of the building elements and energy generation supply are added to identify the total cost. The COP process starts by generating energy demand profiles considering all possible combinations of building elements. Then, each of these energy demand profiles is sent through the hybrid system optimization tool in order to identify the least-cost option for each profile. Consequently, the two costs of building elements and energy supply systems are added up for each combination and the smallest one is selected.

2.3. Tool selection

2.3.1. Selection of building simulation/optimization tool

The BEopt™ (Building Energy Optimization) V 2.2.0.1 efficiency software tool was selected for analysis given its widespread usage in industry and research. BEopt can perform the simulation and optimization of efficiency measures, including building materials and electrical appliances. However, it limits the consideration of energy generation to PV only. Using data on the location of the house, design, characteristics of the building, appliances and other variables, BEopt assesses a range of packages of efficiency measures and determines which offers the lowest cost at a given level of energy savings. For each efficiency measure package, the tool gives the hourly energy demand and total NPC. This NPC includes the cost of the efficiency measures, the cost of energy purchased (included electricity sold back to the grid). Given that the NPC of energy purchased is calculated considering a constant cost of energy (COE) - as if the house was grid-tied - the total NPC for energy generation cannot be considered as the real NPC_{TOTAL} for an off-grid house. The NPC for energy generation calculated by BEopt is referred to here as NPC_{BEOPT}.

2.3.2. Selection of hybrid system optimization tool

HOMER (Legacy Version 2.68) is a simulation software tool that can include a combination of renewable and/or fossil-based generation. The key inputs into the software are a one-year energy demand profile at an hourly resolution, together with profiles of renewable energy resources (wind, solar and hydro). The cost of other fuels (wood, diesel) is also specified, together with their energy properties (MJ per liter or kg). Finally, energy supply components are defined (cost of each PV panel, diesel generator, etc.) as well as their energy supply specifications (power output, fuel consumption, etc.). HOMER then works by conducting multiple simulations, each simulation using a different combination of energy supply components. For each simulation, HOMER evaluates whether or not the energy demand profile has been satisfied, and for those system designs that do satisfy the energy demand over the year, HOMER ranks these in terms of their net present cost (NPC) [19]. Whilst HOMER can consider a range of different energy supply technologies and their associated cost, it does not consider EEM that would result in a decreased energy demand profile.

2.4. Test case

For this research, a hypothetical off-grid house was created to use as a test case. The test case was created from data collected from an actual house located in Cashmere, Christchurch, New Zealand. This allowed the simulated results from BEopt™ to be checked against the observed energy consumption demands of the house, validating the model setup.

The standard process and the COP were applied to the test case. As the standard process contains a degree of variability – selecting packages of EEM based on best practice – our analysis considers five scenarios of the standards process such that the range of possible energy efficiency packages that could be applied, are represented. Finally, to expand the scope of our study beyond one test case, we have applied these analysis once using diesel as the thermal fuel, and then using wood as the thermal fuel. In each case, we compare the results from the standard process and the COP with a base case – where no EEM have been applied.

2.5. Data collection

Data inputs were split into five groups: house specifications, economic inputs, energy sources, hybrid system components, and EEM. All inputs were the same for the base case, standard process, and COP, with the exception of energy demand and efficiency measures. These data inputs were specified in the following subsections.

2.5.1. House specification inputs

Data on the geometry of the house (design and dimensions), location, building materials, appliances, orientation, and operational characteristics were inputs into BEopt. This information was collected from observations of the site and consultation with an engineering expert. For data that was not available, standards defined for NZ cases and values defined by the EEM optimization tool were used. The data not available on-site are specified in the following sections:

- Operation of the house: values defined as default in BEopt for humidity set point and natural ventilation were selected.

Table 3
Sizes and types of hybrid system components.

Component	Sizes considered	Cost $	Replacement Cost $	Operation & Maintenance
Wind	1 kW	13,004	10,403	130 $/year
turbine	2 kW	20,715	16,572	100 $/year
PV	2.2 kW	10,782	8626	216 $/year
array	3.0 kW	14,473	11,579	289 $/year
	4.5 kW	19,337	15,469	387 $/year
	5.0 kW	21,485	17,188	430 $/year
	6.0 kW	25,782	20,626	516 $/year
	8.0 kW	34,376	27,501	688 $/year
	10.0 kW	42,970	34,376	859 $/year
Battery	8 6 V, 900 Ah	7760	6208	312 $/year
bank	12 of 4 V, 1050 Ah	15,520	12,416	384 $/year
	12 of 4 V, 1380 Ah	18,900	15,120	468 $/year
Diesel	1.6 kW	2000	2000	0.050 $/hour
Generator	3.3 kW	6212	4969	0.124 $/hour
	4.25 kW	8000	6400	0.160 $/hour
	5 kW	9412	7529	0.188 $/hour
Converters	2 kW	3000	2401	30 $/year
	3 kW	3348	2678	33 $/year
	5 kW	7900	6320	79 $/year
	7.5 kW	9687	7750	97 $/year

The value for air changes per hour was retrieved from the Building Research Association of New Zealand.

- Building elements: measures of wall elements (spacing, cavity, framing factor and bracing) were retrieved from NZ standards [20]. *R*-values of attic insulation, ceiling insulation, carpet, and wall elements were retrieved from standards [21–25] and consultation with an engineering expert. Characteristics of clay tiles defined as default in BEopt were selected.
- Appliances: values defined as default in BEopt for cooking range and dishwasher characteristics, and operation of the refrigerator, cooking range, dishwasher, cloth washer, hot water and other electrical loads were selected.

BEopt is primarily recommended for simulating a dwelling located in the Northern Hemisphere. To avoid the risk of miscalculating solar angles in the case of a Southern Hemisphere case, simulations were modeled as if they were located in the Northern Hemisphere. Weather data and house orientation variables were modified in order to represent the same house in the Northern Hemisphere. The results delivered by BEopt were then re-organized to represent the house in the Southern Hemisphere. Explicit specification on the case study house, EEM and hybrid systems components can be found in Guerello [26].

2.5.2. Economic inputs

An annual real discount rate (i_r) of 3.81% was defined, using the following formula:

$$i_r = \left(\frac{i_n + 1}{1 + f}\right) - 1 \tag{2}$$

Where i_n is the nominal discount rate and f is the rate of inflation. The discount rate i_n was considered as the average of standard loan interest rates from the banks of ANZ, BankDirect, BNZ, Kiwibank, TSB Bank, and Westpac, which was 6.99%; and the inflation rate as an average of the estimated inflation rates for 2015, 2020 and 2030 [27] of 3.06%. A project lifetime of 25 years was assumed.

2.5.3. Energy source inputs

Solar, wind, wood, and diesel fuel sources were reviewed for the location in Le Bons Bay, Banks Peninsula, Canterbury (stations from the National Institute of Water and Atmospheric Research), where wind and solar energy sources were available and where wind turbines were allowed to be installed. The wind and solar hourly data corresponded to the year 2015, where the daily average solar radiation was 3.87 kWh/m^2/day, and the annual average wind speed was 6.38 m/s. Diesel and wood fuel costs were 0.177 $/kWh and 0.110 $/kWh respectively, and the thermal heating efficiencies were 72% and 76% respectively.

2.5.4. Hybrid system component inputs

Several sizes and types of wind turbines, batteries, diesel generators, and converters were available to the hybrid system optimization tool from which the least cost system design was determined. (see Table 3

2.5.5. Energy efficiency measure (EEM) inputs

The EEM classification) was divided into two groups: building elements (BE), such as adding insulation to walls, ceiling, floor, and installing double glazed windows; and electrical appliances (EA), such as replacing old electrical appliances with more energy-efficient ones. The criteria for selecting the options for each type of EEM were based on the energy efficiency value (*R*-value for building materials and energy star rating for electrical appliances) and on market availability. In the case of building elements, the range of *R*-values was bounded by the minimum *R*-values as defined by the Building Code requirements for the South Island, New Zealand. In the case of appliances, new appliances had lower energy consumption rates or higher energy star rating than the existing ones.

Table 4 shows the EEM chosen for each scenario of the standard process and for the COP with their characteristics (*R*-value or energy rating) and costs. The building elements (BE) and electrical appliances (EA) from the base case are also shown. The Standard Process for minimizing the cost of hybrid systems consists of the application of EEM, followed by the optimization of the Hybrid System size, as explained in Section 2.2. Given that only one choice of EEM could be made for each type of building material and appliance, five scenarios were analyzed, each with different combinations of EEM. The criteria for selecting the options for each type of EEM were based on the availability in the market and on the energy efficiency value: *R*-value for building materials and energy star rating for electrical appliances. The *R*-values of building elements chosen for the five scenarios were higher than the minimum *R*-values defined by the Building Code. In the case of electrical appliances (EA), the energy consumption of electrical appliances chosen for the five scenarios was lower than the base case's appliances. Thus, Scenario 1 consists of the application of cellulose insulation in walls, cellulose insulation in ceilings, fiberglass batt insulation in the ceiling of a crawlspace, and double pane –air fill

Table 4
Specifications for EEM.

		EEM Description	Specifications					EEM applied for each Scenario					
			R-value m^2K/W	Energy Rating (stars)	Energy star mark	Energy use kWh/yr	Cost $/m^2 or $	Base case	Standard Process				
									1	2	3	4	5
Building Elements (BE)	Wall	Uninsulated	0.44	–	–		0	X			X		
		Cellulose insulation in Wall	2.29	–	–		18.4		X	X			
		Cellulose insulation in Wall	2.82	–	–		25.1					X	X
	Roof	Cellulose, Vented insulation in the ceiling	1.94	–	–		0	X			X		
		Cellulose, Vented insulation in the ceiling	3.7	–	–		14.7		X	X			
		Cellulose, Vented insulation in the ceiling	6.69	–	–		24					X	X
	Floor	Uninsulated	0.99	–	–		0	X			X		
		Fiberglass Batt insulation in crawlspace	1.58	–	–		25.2		X	X		X	X
	Windows	Single pane	0.26	–	–		0	X			X		
		Double Pane, non-metal frame, Air Fill	0.36	–	–		652		X				
		Film R-2.04	0.36	–	–		62			X		X	X
Electrical Appliance (EA)	Fridge	Old refrigerator	–	1.5	No	670	809	X				X	
		Mitsubishi, Bottom Freezer	–	2	No	515	1338		X	X			X
		Panasonic, bottom Freezer	–	3	No	413	1635						
		Bosh, bottom Freezer		3	Yes	430	1652						
		Samsung, bottom Freezer	–	3.5	Yes	482	1818				X		X
	Dish washer	Bench mark	–	2	No	204	849	X	X	X		X	
		0.8 Bench mark	–	3.5	Yes	163	1669				X		X
	Clothes Washer	Haier 5.5 kg Top Load Washing Machine	–	1.5	No	490	499	X	X	X		X	
		Beko Washing machine	–	4	Yes	260	850				X		X

Table 5
Results using diesel: standard process and COP results in comparison to the base case.

	Base Case	Standard Process					Combined Optimization Process
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	
NPC_{EEM} ($)	3092	46,233	13,489	5667	15,033	12,313	15,099
Energy Demand (kWh)	22,433	15,307	15,307	21,763	14,846	15,385	14,623
NPC_{HS} ($)	150,653	122,627	122,627	148,011	121,180	122,935	114,913
NPC_{TOTAL} ($)	153,745	168,860	136,116	153,678	136,213	135,248	130,012
Var. vs. Base Case (%)	–	10%	−11%	0%	−11%	−12%	−15%

Table 6
Diesel EEM combinations characteristics.

EEM Package	Building Elements (BE)				Electrical Appliances (EA)				NPC	Energy Savings (%/yr)
	Wall	Ceiling	Crawl sp.	Windows	Refr. 1	Dish W	Clothes W	Refr. 2		
Base Case	U	R 1.94 Cell	U	S	670	Bench	490	670	3092	0,00
EEM-pack 1	U	R 1.94 Cell	U	S	382	Bench	260	382	4460	1.88
EEM-pack 2	U	R 3.7 Cell	U	S	413	Bench	490	413	5563	5.69
EEM-pack 3	R 2.29 Cell	R 1.94 Cell	U	S	382	Bench	490	382	6452	16.58
EEM-pack 4	R 2.29 Cell	R 3.7 Cell	U	S	382	Bench	490	382	8141	21.77
EEM-pack 5	R 2.29 Cell	R 6.69 Cell	U	S	382	Bench	490	382	9202	24.18
EEM-pack 6	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	382	12,647	30.39
EEM-pack 7	R 2.29 Cell	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	382	15,227	33.52
EEM-pack 8	R 2.29 Cell	R 6.69 Cell	R 1.58 FG	Film	382	0.8 Bench	490	382	16,435	33.81
EEM-pack 9	R 2.29 Cell	R 6.69 Cell	R 1.58 FG	Film	515	Bench	490	382	14,893	33.4
EEM-pack 10	R 2.82 Cell	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	382	16,069	34.26
EEM-pack 11	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	382	Bench	260	382	15,559	34.82
EEM-pack 12	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	382	15,336	33.52
EEM-pack 13	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	413	Bench	490	382	15,099	33.49
EEM-pack 14	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	413	15,099	33.47
EEM-pack 15	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	430	Bench	490	382	15,111	33.48
EEM-pack 16	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	430	15,111	33.44
EEM-pack 17	R 2.29 FG	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	515	14,893	33.29

Table 7
NPC_{TOTAL} calculation of EEM l packages using diesel.

EEM package	BEopt Calculation			HOMER Calculation		NPC_{TOTAL}($) = NPC_{EEM} + NPC_{HS}
	Energy savings (%)	NPC_{EEM} ($)	NPC_{BEOPT} ($) (grid tied)	NPC_{HS} ($)	COE ($/kWh)	
EEM-pack 1	1.88	4460	162,373	148,539	1.078	152,999
EEM-pack 2	5.69	5563	157,888	139,313	1.029	144,876
EEM-pack 3	16.58	6452	147,981	129,681	1.035	136,133
EEM-pack 4	21.77	8141	144,473	125,141	1.036	133,282
EEM-pack 5	24.18	9202	143,100	123,025	1.037	132,227
EEM-pack 6	30.39	12,647	140,301	117,662	1.038	130,309
EEM-pack 7	33.52	15,227	139,605	114,936	1.038	130,163
EEM-pack 8	33.81	16,435	140,160	119,701	1.124	136,136
EEM-pack 9	33.40	14,893	140,374	120,204	1.089	135,097
EEM-pack 10	34.26	16,069	139,644	114,220	1.039	130,289
EEM-pack 11	34.82	15,559	140,606	119,804	1.085	135,363
EEM-pack 12	33.52	15,336	139,703	114,936	1.038	130,272
EEM-pack 13	33.49	15,099	139,735	114,914	1.038	130,013
EEM-pack 14	33.47	15,099	139,755	114,913	1.038	130,012
EEM-pack 15	33.48	15,111	139,887	115,091	1.034	130,202
EEM-pack 16	33.44	15,111	139,920	115,233	1.034	130,344
EEM-pack 17	33.29	14,893	140,461	120,355	1.089	135,248

glasses in windows; and the replacement of an old electrical fridge by a 2.0 energy rating fridge. Scenario 2 and 3 represent situations with a combination of pragmatic investments into insulation EAs. Scenario 4 considers settings with top insulation and no investments in EAs and finally, Scenario 5 considers top insulation and investments into high efficient EAs.

For both the diesel and wood cases, the COP delivered a lower cost solution than any scenario using the standard process, with the NPC_{HS} and NPC_{TOTAL} being lower. Details of our findings are presented in the following sections.

3. Results – diesel

Table 5 shows the NPC_{EEM}, NPC_{HS}, NPC_{TOTAL} and energy demand of the base case, the standard processes (scenarios 1–5) and the COP's results where diesel is used as thermal fuel. The COP yielded the lowest cost solution at $130,012, which compared with the standard process value (scenario 2) of $136,116, and the base case scenario of $153,745.

Not only does the COP yield a lower cost solution than the standard process (which involves picking a set of EEM) but the COP yields a lower cost when compared to running the building optimization and simulation program first, followed by the hybrid optimization program. This is explored in Tables 6 and 7 which show 17 of the EEM packages that were explored as part of the COP. From Table 7, the least cost EEM-package as determined by BEopt was package number 7 (NPV of $139,605 assuming the houses is grid-tied, as per the modeling capabilities of BEopt). However, this specific package of EEM does not lead to the lowest NPC when the

Table 8
Results using wood: standard process and COP results in comparison to the base case.

	Base Case	Standard Process					Combined Optimization Process
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	
NPC_{EEM} ($)	3092	46,233	13,489	5667	15,033	12,313	9202
Energy Demand (kWh)	22,433	15,307	15,307	21,763	14,846	15,385	16,715
NPC_{HS} ($)	124,420	107,565	107,565	122,633	106,833	107,643	105,123
NPC_{TOTAL} ($)	127,512	153,798	121,054	128,866	121,866	119,956	114,325
Var. vs. Base Case (%)	–	21%	−5%	−1%	−4%	−6%	−10%

Table 9
EEM combination characteristics using wood.

EEM Package	Building Elements (BE)				EA				NPC_{EEM}	Energy Savings%
	Wall	Ceiling	Crawlsp	Windows	Refrn1	Dish.W	Cloth.W	Refr 2		
Base Case	U	R 1.94 Cell	U	S	670	Bench	490	670	3092	0
EEM-pack 1	U	R 1.94 Cell	U	S	382	Bench	260	382	4460	1.96
EEM-pack 2	U	R 3.7 Cell	U	S	382	Bench	490	382	5818	5.69
EEM-pack 3	R 2.29 Cell	R 1.94 Cell	U	S	382	Bench	490	382	6452	16.31
EEM-pack 4	R 2.29 Cell	R 3.7 Cell	U	S	382	Bench	490	382	8141	21.40
EEM-pack 5	R 2.29 Cell	R 6.69 Cell	U	S	382	Bench	490	382	9202	23.76
EEM-pack 6	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	382	12,647	29.85
EEM-pack 7	R 2.29 Cell	R 6.69 Cell	R 1.58 FG	Film	382	Bench	490	382	15,227	32.91
EEM-pack 8	R 2.29 Cell	R 6.69 Cell	U	Film	430	Bench	490	382	12,531	29.81
EEM-pack 9	R 2.29 Cell	R 6.69 Cell	U	Film	382	0.8 Bench	490	382	13,855	30.15
EEM-pack 10	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	515	12,531	29.77
EEM-pack 11	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	260	382	12,979	31.19
EEM-pack 12	R 2.82 Cell	R 6.69 Cell	U	Film	382	Bench	490	382	13,489	30.59
EEM-pack 13	R 2.29 Cell	R 6.69 Cell	U	Film	413	Bench	490	382	12,519	29.83
EEM-pack 14	R 2.29 Cell	R 6.69 Cell	U	Film	515	Bench	490	382	12,313	29.73
EEM-pack 15	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	515	12,313	29.62
EEM-pack 16	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	515	12,519	29.80
EEM-pack 17	R 2.29 Cell	R 6.69 Cell	U	Film	382	Bench	490	382	12,756	29.85

Table 10
NPC_{TOTAL} calculation of EEM packages using wood.

EEM package	BEopt Calculation			HOMER Calculation		NPC_{TOTAL}($) = NPC_{EEM} + NPC_{HS}
	Energy savings (%)	NPC_{EEM} ($)	NPC_{BEOPT} ($) (grid tied)	NPC_{HS} ($)	COE ($/kWh)	
EEM-pack 1	1.96	4460	136,009	123,160	1.100	127,620
EEM-pack 2	5.69	5818	132,750	114,777	1.053	120,595
EEM-pack 3	16.31	6452	126,502	109,094	1.054	115,546
EEM-pack 4	21.40	8141	124,753	106,385	1.055	114,526
EEM-pack 5	23.76	9202	124,195	105,123	1.055	114,325
EEM-pack 6	29.85	12,647	123,501	101,923	1.056	114,570
EEM-pack 7	32.9	15,227	123,861	100,296	1.056	115,523
EEM-pack 8	29.81	12,531	123,805	102,133	1.051	114,664
EEM-pack 9	30.15	13,855	124,101	107,187	1147	121,042
EEM-pack 10	29.77	12,531	123,826	102,217	1.051	114,748
EEM-pack 11	31.19	12,979	125,022	107,727	1.104	120,706
EEM-pack 12	30.59	13,489	123,795	101,502	1.056	114,991
EEM-pack 13	29.83	12,519	123,644	101,904	1.055	114,423
EEM-pack 14	29.73	12,313	124,328	107,643	1.110	119,956
EEM-pack 15	29.62	12,313	124,388	107,726	1.110	120,039
EEM-pack 16	29,80	12,519	123,659	101,903	1.055	114,422
EEM-pack 17	29.85	12,756	123,599	101,923	1.056	114,679

design and cost of the hybrid system are taken into account, instead, EEM-package 14 yields the lowest global minimum of NPC. It should also be noted that EEM package 14 does not have the lowest energy consumption, hence showing that there are some energy efficiency measures where the cost of the energy efficiency measure is greater than the cost of energy that is saved under the economic conditions of this study (discount rate and lifetime of the project).

4. Results - wood

Table 8 shows the NPC_{EEM}, NPC_{HS}, NPC_{TOTAL} and energy demand of the base case, the standard process (scenarios 1–5) and the COP's results where wood is used as the thermal fuel instead of diesel. Again, the COP yielded the lowest cost solution at $114,325, which compares with the standard process value (scenario 5) of $119,959 and the base case scenario of $127,512. Furthermore, in this case, the COP solution is one that results in higher energy consumption compared to all but one of the standard process results. This is due to the lower cost of wood energy compared to diesel, making it more cost-effective to simply consume a greater amount of fuel keeping the home at the desired temperature, rather than over-investing in insulation measures.

Tables 9 and 10 again show that determining the EEM first (using a building optimization tool) followed by the determination of the hybrid system, does not yield the least cost system overall. In

Table 10, package 6 of EEM yields the lowest NPC cost as determined from BEopt), however, this leads to a total NPC of $114,570, which is higher than EMM package 5 at $114,325.

The central finding of our analysis is that the COP delivered a lower cost solution than any scenario considered in the standard process, demonstrating that joint optimization of EEM and hybrid systems can give a better solution than the sequential application of EEM followed by hybrid optimization.

The second finding is that the EEM package with the lowest energy demand solution does not guarantee the lowest cost solution in terms of the total system. This is because the size and characteristics of the hybrid system depend not only on the total annual energy demand but also on the hourly profile of demand.

The third finding is that the most optimal solution from the EEM optimization tool is not necessarily the overall optimal solution, meaning that optimizing EEM first using a constant cost of energy, and then optimizing the hybrid system does not guarantee the lowest cost solution. This study thus builds on the work of Thompson and Duggirala [28] who performed an energy efficiency audit to identify low-cost EEM and then calculated and compared different configurations of hybrid systems. The process applied by Thompson and Duggirala [28] could be interpreted as sequential optimization of EEM followed by optimization of the hybrid system. A similar approach to this interpretation was carried out in Steps 2 and 4 of the COP, where all the possible EEM packages were input into the EEM optimization tool, which calculated the optimal package of EEM (package 7 in Table 6) using a constant cost of energy (COE). However, when calculating the optimal hybrid systems of these EEM packages, the NPC_{TOTAL} (total NPC of the system: NPC_{HS} plus NPC_{EEM}) were not the optimal ones. This may be due to the fact that because all packages of EEM modeled in the EEM optimization tool were assumed to have the same cost of energy while, in reality, each package of EEM would have a different COE, due to its particular energy demand profile and configuration of the hybrid system.

5. Limitations of the study

We recognize a number of limitations in the study: limitations in the selection of optimal packages, assumptions related to household behavior, no consideration given to changes in the operation of the hybrid system, and limitations related to a single case study.

Firstly, all packages of EEM modeled in BEopt were assumed to have the same cost of energy, while in an off-grid house, each package of EEM may have a unique cost of energy, due to its particular energy demand profile and configuration of the hybrid system. Considering that the optimal EEM calculated by BEopt did not guarantee the lowest cost solution in terms of the total system, each EEM package from BEopt should be analyzed in HOMER. However, due to limitations in calculation processing capacity, only a cluster of EEM packages was selected, based on the lowest total NPC_{BEOPT} calculated by BEopt. Between ten and eleven optimal EEM packages (close to the one with the lowest NPC_{BEOPT}) were selected to be analyzed in HOMER for both cases. Considering that this cluster of EEM packages was among the optimal ones calculated by BEopt, it is likely that the optimal solution in terms of HOMER was also between the EEM packages selected. To ensure obtaining the absolute optimal EEM package, each EEM package from BEopt could be analyzed in HOMER.

Secondly, the assumption that households would not change their energy consumption behavior, hence resulting in a different low profile. It is possible, however, that households may, for instance, use appliances in a more efficient way or change their energy demand according to energy supply availability, factors which are excluded from the optimization model. Household behavior could be represented in BEopt with a different operation schedule for appliances, for instance, usage when renewable energy is available (thereby avoiding the cost of diesel-generated power), resulting in a lower cost of energy. If no investment cost is required to change consumer behavior in pursuit of a lower energy cost, it would be the cheapest EEM. Explicit modeling of consumer behavior could thus yield a combined optimization process that identifies a better solution than the standard process or the COP that excludes behavioral change.

Thirdly, the operation of the hybrid system has been held constant for all cases. If different management strategies were applied, such as under what conditions the batteries are charged and/or switched on/off, the COP process may have identified an alternative system with an even lower cost. In summary, the optimization of the HS operation has not been considered. Additionally, optimal control strategies of energy-demanding components (such as heating appliance, refrigeration) have not been considered.

Finally, only a single case study building has been analyzed. Therefore, we cannot claim that COP will in all cases guarantee results with cost-saving when compared to the standard process. However, it will not produce a worse result because it examines many potential solutions, one of which may have been found using the standard process.

6. Future research

An improvement in the COP would be the development of a software tool that is able to combine the optimizations calculations of BEopt and HOMER. In other words, a tool that can calculate the optimal hybrid system for each of the EEM packages. This new tool should be able to calculate the energy demand for each package of EEM, as well as calculate the optimal hybrid system for each of the energy demand profiles.

An alternative to the development of a new tool would be the addition of hybrid system components to BEopt in order to perform 100% off-grid analysis. Instead of considering a constant cost of energy (grid electricity), total electric demand could be generated by the components of a hybrid system. Likewise, a geometry interface could be added to HOMER to perform energy demand and energy efficiency simulations in order to reduce the load and to find the optimal hybrid system.

Modeling household behavioral change could also be incorporated into these new tools as another type of EEM or as a new option for appliance operation schedules. The impact of the household's behavior would be seen in the hourly profile of energy demand, which would be analyzed in the hybrid system. The possibility of changing demand profiles according to the energy available on the hybrid energy system could identify lower-cost hybrid systems than the ones calculated with current software tools.

Finally, in determining the actual optimal package for a specific case study, a sensitivity analysis would benefit the robustness of the actual result produced. In this paper, the objective of this study was to determine the benefit of the proposed COP method rather than the specific results of the hypothetical case.

7. Conclusion

This paper investigates the impact of a new analytical method – the COP - to evaluate potential energy cost-savings in off-grid houses, and compares it against a standard approach. The analysis suggests that the standard approach, which sequentially applies EEM followed by hybrid system optimization, does not necessarily yield the least cost energy technology solution because it does not fully account for the impact of alternative EEM packages on the hybrid system. To illustrate the differences, two processes were evaluated for a hypothetical off-grid house: the combined optimization process, which comprised an analysis of various different packages of EEM and hybrid systems and an overall evaluation of the optimal solution in terms of net present cost (NPC); and the standard process, which consisted of the application of EEM, followed by hybrid system optimization. For each case analyzed, the COP provided a lower cost solution than the standard process. The COP optimized over both EEM and the hybrid system to find the overall cheapest energy generation system for an off-grid house. While the proposed COP demonstrates improvement in standard practices, there are nonetheless several limitations that may be addressed in future research.

Declaration of Competing Interest

We declare that there are no conflict of interests associated with our submitted manuscript titled as Energy for off-grid homes: Reducing costs through joint hybrid system and energy efficiency optimization.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.109478.

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