FEASIBILITY ANALYSIS OF A PHOTOVOLTAIC/ BATTERY ENERGY STORAGE HYBRID SYSTEM: AN HOURLY ESTIMATION BASED APPROACH AND A REAL LIFE CASE STUDY

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ABSTRACT

This study has been undertaken to develop a consumer-oriented feasibility method for a hybrid photovoltaic (PV)-battery energy storage (BES) system by analyzing a real life house in Istanbul, Turkey, as a case study. The hourly electricity demand of the house was estimated by carrying out a detailed survey of the life style and daily habits of the household. No algorithm of any kind was used for the estimation of the energy demand with the exception of relating the lighting requirement to the daylight hours and the heating and cooling requirements to the seasonal weather changes. The developed method estimates the annual demand with an overall error of 8.68%. The net grid dependency and the feasibility of the PV-BES system was calculated for different combinations of PV and BES system sizes. It was found that when the maximum available roof area is used for PV installation and when the BES system size is increased, it is possible to achieve almost zero net grid dependency, and it is estimated that houses that are in regions with more abundant solar radiation and/or with lower annual electricity consumption, can reach zero net grid dependency. However, the feasibility indicator, which is the payback period, turned out to be no less than 25 years in any of the scenarios. The reasons for the infeasibility are the high prices of PV and BES systems as well as the current restriction in the regulations in Turkey, which prevents BES system owners from participating in unlicensed energy generation schemes and selling excess electricity back to the grid. In order to overcome this situation, regulations should be updated to allow BES system owners to benefit from feed-in-tariff schemes, thereby increasing the popularity of both PV and BES usage in Turkey.

KEYWORDS

photovoltaics, battery energy storage systems, feasibility, Turkey

1. INTRODUCTION

Over the last few decades the use of renewable energy sources has been increasing on a global scale. Some of the driving factors for this trend are concerns about the security of energy supply,

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desire for more efficient transmission of energy, need for maximizing the utilization of local resources and thereby improving national economies, and also efforts at decreasing climate-change-causing CO_2 emissions, most of which result from fossil fuel use (Cheng, Chiu, Lien, Wu, & Lin, 2016). Considering that worldwide energy demand is expected to grow by 25% by 2040, it can be concluded that renewable energy technologies will continue to bear significance in the global energy portfolio (ExxonMobil, 2016). Amongst renewable energy sources, photovoltaic (PV) solar energy offers great potential for use in building systems due to several reasons. Photovoltaic systems convert sunlight to electricity silently and without moving parts, require little maintenance, are reliable, are being sold with warranties of up to twenty-five years, generate no greenhouse gases in operation. Their modular and rapidly deployable structures particularly suit urban rooftops, façades, and similar applications (Corkish & Prasad, 2006). Building systems are responsible for roughly 40% of global energy consumption (Üçtuğ & Yükseltan, 2012), thus reducing the grid-dependence of buildings by using PV systems would bring enormous economic and environmental benefits (Syed & Abdou, 2016). However, PV systems have two main disadvantages. Firstly, they are relatively expensive systems. The United States Energy Information Administration states that PV systems have higher levelized cost of electricity values than any other commercially available renewable or non-renewable energy technology, with the exception of offshore wind and concentrated solar power technologies (EIA, 2016). Nonetheless, the prices of PV systems have decreased considerably in recent years and as a result they have become more affordable (Jäger-Waldau, Szabó, Monforti-Ferrario, Bloem, Huld, & Arantegui, 2012). The second and the main problem regarding PV systems is their intermittency. PV systems cannot generate electricity in a continuous, reliable manner, as solar radiation may not be present at all or it may not be at the desired level at any time during the day. Therefore, the following situations are observed quite often: PV systems fail to meet the instantaneous demand during most of the day, or PV systems generate much more electricity than the instantaneous demand during certain times of the day. Hence, coupling the PV system with a battery is essential if net zero grid dependency is targeted in building systems (Jossen, Garche, & Sauer, 2004). Using batteries would enable the household to store the excess electricity generated during low-demand hours and then use this electricity at any time during the day when generation fails to match demand. Battery energy storage (BES) systems are also quite expensive, therefore it is important that a carefully-devised feasibility analysis is performed before making the decision whether to couple a PV system with a battery system or not. To that end, in this study, a novel method that takes the 8760-hour PV electricity generation data into account and estimates the 8760-hour load data of a single family home over an entire calendar year has been developed. The purpose of this study is to create a novel method that analyzes whether it is possible to reach zero grid dependency, and if not, how much of a reduction in grid dependency can be achieved. The model also calculates the feasibility of the system. The details of the method can be found in the following sections.

2. LITERATURE REVIEW

There are several studies in which the economic analysis of grid-connected or stand-alone PV-battery systems for domestic applications have been investigated. Gitizadeh and Fakharzadegan proposed a method to determine battery capacity in a grid-connected PV/storage system with respect to optimal scheduling of the battery by using fuzzy clustering method. They found that sizing optimization for a battery used in a PV/storage system highly depends on electricity rates and battery ageing cost (Gitizadeh & Fakharzadegan, 2014). Bortolini et al. developed a techno-economic model for the design of a grid-connected photovoltaic system with battery energy storage. The proposed model is based on a power flow control algorithm oriented to meet the energy load profile initially with a PV–BES system. The model aims to minimize the levelized cost of the electricity (LCOE) of the PV–BES system by using the hourly energy demand profile, the hourly available irradiation, and the temperature levels measured at the installation location as the main inputs (Bortolini, Gamberi, & Graziani, 2014). Hanna et al. created a battery storage dispatch strategy that optimizes demand charge reduction in real-time, and they simulated the discharge of battery storage devices in a grid-connected, combined photovoltaic-battery storage system for one summer and one winter month, in an operational environment (Hanna, Kleissl, Nottrott, & Ferry, 2014). Cucchiella et al. evaluated the profitability of mono-crystalline PV systems in the residential sector without subsidies, and subsequently evaluated the profitability of lead-acid BESs. They employed a quantitative analysis method based on discounted cash flows and a sensitivity analysis on the following critical variables: the PV system sizes, electricity purchase prices, electricity sales prices, investment costs of PV systems, specific tax deductions, levels of insolation, shares of self-consumption, battery storage capacities, estimations of the battery cost, the useful time of a battery, and increases of self-consumption following the adoption of an energy storage system (Cucchiella, D'Adamo, & Gastaldi, 2016). Yoshida et al. investigated the operation of a photovoltaic/grid, electric/battery system in a house in terms of cost savings and energy savings by developing a long-term operational optimization model considering the degradation characteristics of the battery. Their model had two objective functions, which were energy savings and operating costs. They studied a scenario of power rates and photovoltaic/battery system configurations. In order to obtain the optimal operational strategy for the photovoltaic/battery system, the multi-objective optimization problem was solved. As a result, Pareto-optimal solutions were obtained and trade-off relationships between cost and energy savings were presented. They concluded that the utilization of a grid-connected photovoltaic system with a battery proved to be more effective in an energy-saving priority operation when compared to purely grid based and PV-grid based systems (Yoshidaa, Satob, Amano, & Ito, 2016).

With respect to standalone PV-BES systems, Kazem et al. worked on the optimal sizing of a standalone PV system in Oman; they used a numerical method and hourly meteorological data. Loss of load probability (LLP) was used as a reliability parameter and the best configuration was determined by minimizing the capital investment required for the system. The authors mentioned the PV array sizing ratio, storage battery sizing ratio for the selected location, and the cost of energy (Kazem, Khatiba, & Sopian, 2013). Chen and Bayesian published a paper on the optimization of a standalone PV system. A comprehensive economic optimization containing capital, maintenance, and penalty costs of the alternative configurations was presented. Their model minimized the annualized total cost by using daily average meteorological data and load demand as inputs (Chen, 2013). Lee et al. developed a model which uses solar resource, energy demand, and component cost data as inputs. The model then computed cost versus a reliability curve of annual performance for potential micro-grids and chose a point on cost versus reliability curve on which to conduct temporal analysis. After computing reliability during each month, the model picked the lowest reliability month(s) and performed an analysis at a sub-daily time scale. If performance and cost are acceptable, then the design was concluded, if not, iterations would be continued (Lee, Soto, & Modi, 2014). Bouabdallah et al. investigated the safe techno-economic sizing methodology of a standalone photovoltaic system. They used Markov transition matrices (MTM) to simulate stochastic cloud cover sequences. Each sizing was then tested on a large number of scenarios. Annual load profiles were obtained from one typical day per month (Bouabdallah, Olivier, Bourguet, Machmoum, & Schaeffer, 2015). In the paper published by Erdinc et al., the home energy management structure and thus the daily operation of a smart household was associated with the sizing procedure under a mixed-integer linear programming modeling framework, pertaining to a long-term horizon. The household load demand was provided in a retrospective manner by considering power values of real household appliances for a previous smart home demonstration project (Erdinc, Paterakis, Pappi, Bakirtzis, & Catalao, 2015). Nordin and Rahman suggested a new method for the optimal sizing of a standalone photovoltaic system by using amp-hour analysis. Optimal PV capacity, battery capacity, charge controller rating, inverter rating, and components connection were determined based on the lowest levelized cost of electricity that are able to fulfill loss of power supply probability system requirements (Nordin & Abdul Rahman, 2016).

Finally, two studies published by the same research group have been reviewed. In the first paper (Bianchi, Branchini, Ferrari, & Melino, Feasibility study of a Thermo-Photo-Voltaic system for CHP application in residential buildings, 2012), Bianchi et al. studied the feasibility of a thermal-photovoltaic system for combined heat and power (CHP) applications in residential buildings. In the second paper (Bianchi, Branchini, Ferrari, & Melino, Optimal sizing of grid-independent hybrid photovoltaic–battery power systems for household sector, 2014), which is more relevant to this paper, Bianchi et al. realized the optimization of a PV/BES hybrid system design in terms of PV module number, PV module tilt, number and capacity of batteries with the purpose of minimizing or, if possible, neglecting grid supply. The method described in both papers, which is explained in detail in the following section, bears certain resemblances to the approach used by Bianchi et al. in the sense that both methods rely on obtaining 8760-hour PV electricity generation data and specific 8760-hour household electricity consumption data for the studied house. However, in their study Bianchi et al. determined the electrical load curve by considering the overlap of the various appliances which, on average, can be found in an Italian house (where the analysis takes place): lighting, computers, cooling and heating appliances, cleaning appliances, and audiovisual devices. By contrast, the scope of this particular study aims to obtain a more accurate, customized load profile by interviewing the household about their lifestyle. Furthermore, the method is created with the purpose of analyzing whether it is possible to reach zero grid dependency while simultaneously performing a feasibility analysis of the system whereas Bianchi et al. tried to minimize the supply coming from the grid, like many other studies concerned with the optimal sizing of the PV/BES system. Therefore, for all the reasons mentioned above, it is believed that the approach used in this study is novel.

3. METHODOLOGY AND CASE STUDY

In this section, the methodology that was used to determine feasibility of a BES system to be used alongside a PV system in order to achieve net zero grid dependency is described. A case study analysis, which was carried out on a real house located in the Zekeriyaköy region of Istanbul, Turkey, will also be included so that the readers can better understand the method. The case study began on the 1st of July, 2015, and ended on the 30th of June, 2016.

3.1. Determination of PV output and load profile

The 8760 hour PV data was obtained from "*http://pvwatts.nrel.gov/pvwatts.php*". In the literature it is suggested that a maximum of 60% of the available roof area can be used for PV panel installation without risking structural safety (Melius, Margolis, & Ong, 2013). Thus, the maximum PV system capacity was found by using this approach. A market analysis revealed that the average power density of polycrystalline PV systems is around 150 W/m^2 (PVLighthouse.com, 2016). Thus, the highest possible nominal wattage of the PV system was determined as follows:

$$W_{PV,max} = A_{roof} \times 0.6 \times 0.15 \tag{1}$$

where $W_{PV,max}$ is the wattage of the PV system in kW, and A_{roof} is the available roof area in m^2. In this particular study, the effect of the PV system size on feasibility was analyzed, and the maximum possible PV installation area is limited by Eq.(1).

The parameters required for hourly PV output are provided in Table 1 below. Recall that the aim of this particular study is to develop a method that would calculate the capacity of the BES system required for achieving the lowest possible grid dependency and the parameters associated with the PV system are completely independent of the method. In Table 1, only the data used in the case study are presented, however, for any other analysis these figures may be completely or partially different.

The value of the system losses was taken as 15%, which is the default amount suggested by the calculator. The tilt area depends on the rise/run ratio of the roof, as explained by the developers of the solar energy output calculator used in this study. Considering the climatic conditions in the region of our case study and by referring to previous literature (Üçtuğ & Yükseltan, 2012), the rise/run ratio of the house was determined as 8/12, which would yield a tilt angle of 33.7°. Finally, the azimuth degree, which depends on the orientation of the location, was taken as 180° as the house in the case study faces south.

While it is acknowledged that forecasting the hourly load of a household throughout an entire year is very difficult, it is considered that if the forecasting is carried out in a realistic and meticulous manner, this is the most accurate way of determining the feasibility of PV-BES systems. A similar opinion has been brought forward by Linssen et al., who recommended "*using realistic load profiles as the basis for modelling, system design and battery selection, while using aggregated profiles (e.g. standard load profiles) is not advised as this may lead to optimization*

TABLE 1. Parameters required for the calculation of the PV system output in the case study.

Parameter	Value
Array Type	Fixed (roof top)
System Losses (%)	15
Tilt (degrees)	33.7
Azimuth (degrees)	180
Roof Area (m^2)	144
Maximum PV System Size (kW)	13

results, which are too optimistic in terms of total costs and required battery size" (Linssen, Stenzel, & Fleer, 2015).

The 8760-hour load profile was determined by conducting an in-depth survey of household members. Before that, the electricity consumption data (in Watts) of every single electrical load in the house was gathered. All the appliances, all the lighting equipment, etc. were noted and later their electricity consumption data were obtained either from their labels or from the websites of the manufacturing companies. The purpose of the survey was to gather information about the daily life habits of the household. Several questions were asked regarding their eating, working, leisure, and sleeping hours; how often and usually at what time of the day they use particular appliances such as dishwashers, washing machines, dryers, etc.; how often they charge their mobile phones, whether they leave certain devices on standby mode or completely turn them off while not using them, and so on. The answers given to these questions, together with the seasonal changes of lighting, heating, and air conditioning requirements, were then used to prepare a Microsoft Excel worksheet which would combine the hourly electricity generation and consumption data of the house. It must be noted that any kind of algorithm (aside from relating the effect of sunset hour to lighting usage) was not developed for the determination of the load profile. Instead, it was assumed that the household would display the same habits throughout the year, with the exception of the ones that are season-dependent (such as the use of air conditioners or lighting). The details regarding this worksheet, which is also the main tool that was used to determine the feasibility of the combined PV/BES system, will be explained in the following part (sub-section 3.2).

While the load profile of the house could be obtained in a much more accurate manner by using smart plugs and by relying on retrospective data, the feasibility analysis in that case would take much longer as the electricity consumption is strongly influenced by seasons and climatic conditions, which would require a full year's data before reaching any conclusions. Since the studied house is not a smart house, it was not technically possible to test the accuracy of our load estimation approach in detail. Instead, the estimated consumption values obtained for each month are summed up and compared with the actual electricity bills of the house for the previous year. The results of this comparison are presented in the Results and Discussion part (sub-section 4.1).

3.2. Selection & sizing of the battery energy storage system and economic analysis

Different battery types can be used for domestic applications, such as lead-acid, NaS, and Li-ion batteries. When the key properties of these battery types are compared, it can be seen that Li-ion batteries are superior when it comes to performance, with higher power density, energy density, and durability scores than most other battery types (Rudolf & Papastergiou, 2013). The main setback, however, of Li-ion batteries is the relatively high cost (Hall & Bain, 2008). In this study, a Li-ion battery system was preferred due to performance being the main selection criteria. The selected product was Powerwall® by Tesla®.

The worksheet that was created for the economic analysis contains a total of 8766 rows (for any analysis) and the number of columns depends on the number of electrical appliances in the house. Thus, it would be practically impossible to insert it into this paper. Instead, an oversimplified version of the worksheet, for the first day of the analysis and with only five electrical appliances present in the house (which is clearly unrealistic but assumed for the sake of simplicity), is provided below in order to explain how it is used.

Before proceeding with the explanation of the calculation table, the manner in which any cell within the table will be referred to is described. Let us define an arbitrary cell (C_5,R_5). In this notation C stands for column and R stands for row. Hence, (C_5,R_5) happens to be the cell intersecting the fifth column with the fifth row. In Table 2, the numerical values written below each device (C_4 to C_8, R_2) are the electricity consumption value of that particular device, in Watt units, obtained either from its label or from the Internet. The numbers below this row are binary operators. If the device is being used at that hour, then the cell gets a number "1", if not then number "0" is entered. When Table 2 is inspected, it can be seen that there are five devices with different characteristics: Device A is not operated during early morning and daylight hours, and then it is operated continuously during the evening and night, which is the typical operation characteristic of a light bulb. Device B is operated continuously throughout the day; therefore, it is the refrigerator. Device D is operated only for two hours in one day, which is the typical operation characteristic of an on-demand type appliance such as dishwasher, washing machine, iron, personal computer, etc. At this stage, the readers might (rightfully) question the presence of values other than 1 or 0 in a binary table, as in the cases of Device C and Device E. Device C is operated continuously during the day, but with different consumption values during different hours. Thus, Device C is an appliance which is left on standby mode while not being used, and then operated on demand during certain hours of the day, such as a television or a satellite receiver (ideally from an energy-conservation point of view all such devices should be completely turned off instead of being left on standby mode while not being used, but our survey revealed that the behavior pattern of this particular household is otherwise). It is known that a typical flat screen television consumes approximately 25% of its nominal power requirement while on standby mode, and that is why the value of 0.25 is inserted in the corresponding cells (C_3, R_3 to R_{20}). Finally, Device E is operated only twice during the day, and the number inside the corresponding cells is 0.05 (C_8, R_{10} & R_{24}). This number does not come from the low energy consumption of the device but from the short usage duration. Device E is actually a water heater (kettle), whose operation usually takes around 3 minutes. Three minutes is 1/20th of an hour, and that is why a value of 0.05 was inserted in the corresponding cells.

The values in column 9 are the total electricity consumption of the house for each hour. The formula used for this calculation is as follows:

$$\mathrm{Value}(C_{n+1},R_i) = \sum_{j=4}^{n}\left[Value\left(C_j,R_2\right)Value\left(C_j,R_i\right)\right]/1000 \tag{2}$$

In Eq.(2) above, C and R indicate columns and rows, respectively; while *j* and *i* are column and row indices, respectively. Finally, *n* is the last column for electrical appliances (in this example, n corresponds to column 8). Hence, $n + 1$ becomes the column in which the total electricity consumption of the house is presented. Let us verify the equation for the first hour of January 1st:

$$\mathrm{Value}(C_9,R_3) = \sum_{j=4}^{8}\left[Value\left(C_j,R_2\right)Value\left(C_j,R_3\right)\right] =$$

$$[(20\times0) + (80\times1) + (50\times0.25) + (2000\times0) + (2000\times0)] / 1000 = 0.0925 \text{ kWh}$$

TABLE 2. Load estimation and BES sizing worksheet (oversimplified example – PV system capacity: 13 kW, BES system capacity: 19.2 kWh).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
R1				Device A	Device B	Device C	Device D	Device E	Total Consumption (kWh)	PV Generation (kWh)	Storable electricity (kWh)	Electricity supplied by non-PV (kWh)	Energy stored in BES system (kwh)	Net supply to/from BES (kWh)	Net supply from BES (kWh)
R2	Month	Day	Hour	20	80	50	2000	2000							
R3	January	1	1	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R4			2	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R5			3	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R6			4	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R7			5	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R8			6	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R9			7	0	1	0.25	0	0	0.0925	0.000	0.000	0.0925	0.000	0.000	0.000
R10			8	0	1	0.25	0	0.05	0.1925	0.000	0.000	0.1925	0.000	0.000	0.000
R11			9	0	1	0.25	0	0	0.0925	1.380	1.2875	0.000	1.2875	1.2875	0.000
R12			10	0	1	0.25	0	0	0.0925	3.479	3.3865	0.000	4.6740	3.3865	0.000
R13			11	0	1	0.25	0	0	0.0925	4.710	4.6175	0.000	9.3455	4.6715	0.000
R14			12	0	1	0.25	0	0	0.0925	6.174	6.0815	0.000	15.427	6.0815	0.000
R15			13	0	1	0.25	0	0	0.0925	7.253	7.1605	0.000	22.5875	7.1605	0.000
R16			14	0	1	0.25	0	0	0.0925	7.293	7.2005	0.000	29.788	7.2005	0.000
R17			15	0	1	0.25	0	0	0.0925	4.764	4.6715	0.000	34.4595	4.6715	0.000
R18			16	1	1	0.25	0	0	0.1125	1.712	1.5995	0.000	36.059	1.5995	0.000
R19			17	1	1	0.25	0	0	0.1125	0.042	0.000	0.0705	35.9885	-0.0705	0.0705
R20			18	1	1	0.25	0	0	0.1125	0.000	0.000	0.1125	35.876	2.8875	0.1125
R21			19	1	1	1	0	0	0.150	0.000	0.000	0.150	35.726	-0.15	0.15
R22			20	1	1	1	1	0	2.150	0.000	0.000	2.150	33.576	-2.15	2.15
R23			21	1	1	1	1	0	2.150	0.000	0.000	2.150	31.426	-2.15	2.15
R24			22	1	1	1	0	0.05	0.250	0.000	0.000	0.250	31.176	-0.25	0.25
R25			23	1	1	1	0	0	0.150	0.000	0.000	0.150	31.026	-0.15	0.15
R26			24	1	1	1	0	0	0.150	0.000	0.000	0.150	30.726	-0.3	0.3

The values in column 10 are the hourly electricity generation via the PV system, in kWh units. Column 11 contains the amount of electrical energy that can be stored in the battery. Naturally, storage is possible only when the generated amount is greater than the hourly demand, and storage would be equal to the difference between generation and demand; otherwise, storage would be zero. Thus, the following formula was used to calculate the values for all the cells within Column 11:

$$\begin{gathered}\text{IF } [\text{Value}(C_{10},R_i) > \text{Value}(C_9,R_i)],\\ \text{THEN Value}(C_{11},R_i) = [\text{Value}(C_{10},R_i) - \text{Value}(C_9,R_i)],\\ \text{ELSE Value}(C_{11},R_i) = 0\end{gathered} \tag{3}$$

Column 12 indicates the amount of electricity that the household needs from sources other than the PV system for any hour. The values within Column 12 would be positive if the hourly consumption exceeds the hourly generation, they would be zero otherwise. The formula used for the calculation of the values within Column 12 is as follows:

$$\text{Value}(C_{12},R_i) = \text{MAX } [(\text{Value}(C_9,R_i) – \text{Value}(C_{10},R_i)); 0] \tag{4}$$

Column 13 is the net amount of energy stored in the BES system. For the first hour of the first day of the analysis, this value would be equal to:

$$\text{Value}(C_{13},R_3) = \text{Value}(C_{11},R_3) \tag{5}$$

For all the remaining 8759 hours of the year and for any hour of the following year, the formula given below is used in order to calculate the values within Column 13:

$$\text{Value}(C_{13},R_i) = \text{MAX } [(\text{Value}(C_{13},R_{i-1}) + \text{Value}(C_{11},R_i) – \text{Value}(C_{12},R_i); 0] \tag{6}$$

According to the formula above, the net amount of energy stored in the BES system in any hour is equal to the sum of the amount of energy already stored by the end of the previous hour and the difference between the storable amount of energy and required amount of energy. If this value turns out to be negative, the cell simply gets a value of zero, since it is impossible to store negative electricity.

Column 14 shows the net supply from/to the BES system, and it is defined as follows:

$$\text{Value}(C_{14},R_i) = \text{Value}(C_{13},R_i) – \text{Value}(C_{13},R_{i-1}) \tag{7}$$

If a cell within Column 14 has a positive value, it means energy is stored in the BES system; on the other hand, a negative value means energy discharged from the BES system into the house. Therefore, only the negative values shall be considered when it comes to calculating the energy supply from the BES system. Column 15 is used for that purpose:

$$\begin{gathered}\text{IF Value}(C_{14},R_i) < 0\\ \text{THEN Value}(C_{15},R_i) = -1 \times \text{Value}(C_{14},R_i)\\ \text{ELSE Value}(C_{15},R_i) = 0\end{gathered} \tag{8}$$

By using Eq.(8), the amount of electrical energy supplied from the BES system into the house can be calculated (the presence of a "-1" factor in Equation (8) makes all these values positive). Hence, when all the values within column 15 are summed, the total annual energy supply from the BES system can be calculated.

Normally, the sizing of the BES system would be determined as follows: The values within column 13 indicate the cumulative energy storage within the BES system. These values can increase, decrease, or remain the same depending on the relative values of instantaneous generation and consumption. The sizing of the BES system would be the maximum value within column 13, unless this value exceeds the actual storage capacity of the system. However, Tesla® Powerwall® does not offer different sizing options since March 23rd, 2016 (the situation was different and there was more than one option when this particular study started). The only available option is the 6.4 kWh system and therefore the BES system size will be fixed at this value or its integer factors (12.8 kWh, 19.2 kWh, etc.).

The feasibility of the system was evaluated by using the payback period, which is a commonly accepted means of feasibility evaluation for small scale investments and used in several similar studies (Kaldellis, et al., 2010; Khoury, et al., 2015; Mulder, et al., 2013). The payback period of investment was calculated as follows:

$$\mathrm{PP} = \frac{\sum_{i=3}^{n} Value\left(C_{15},\ R_i\right)\ P_{elec}}{INV} \tag{9}$$

where PP is the payback period of investment (years), n is the total number of rows in the spreadsheet (8766, as indicated above), P_{elec} is the price of grid electricity ($/kWh) and INV is the initial investment required for the PV and BES systems combined ($).

The net grid dependency was calculated as follows: The house can be supplied electricity from three different sources: the PV system, the BES system, or the grid. Table 1 provides the data for electricity supplied from the PV system or the grid. Thus, if these two values for the entire year are added and then if the summation is subtracted from the annual demand, the electricity supplied from the grid can be found. When this value is divided by the annual demand, the net grid dependency ration would be obtained. The formulation can be found below:

$$\mathrm{NGD} = \frac{TAD - \left(\sum_{i=3}^{n} Value\left(\left(C_{15},\ R_i\right) + PVS_i\right)\right)}{TAD} \times 100 \tag{10}$$

$$\text{IF Value}(C_{10},R_i) \geq \text{Value}(C_9,R_i) \text{ THEN } PVS_i = \text{Value}(C_9,R_i)$$

$$\text{ELSE } PVS_i = \text{Value}(C_{10},R_i)$$

In the equations above, TAD stands for total annual demand (kWh) and PVS stands for electricity supplied from the PV system (kWh).

4. RESULTS AND DISCUSSION

4.1. Accuracy of load estimation

The accuracy of the method developed for load estimation was tested by comparing the initial monthly estimates with the actual monthly electricity bills for the previous year. It is shown in Table 3 that the overall error is 8.68%. An overall error less than 10% is regarded as satisfactory for this kind of predictive analysis. If the error had been calculated based on the total estimated and actual consumption values, it would have been only 3.5%. However, this would be misleading as in some months the estimation exceeds the actual consumption whereas in others the actual consumptions are higher than our estimations. To account for positive and negative errors at the same time, the relative errors were calculated for each month and then their average was taken to get the overall error for our estimation method. There is a considerable difference between our estimations and the actual consumption only in the month of August. As mentioned before, our prediction method is based on the lifestyle of the household. When they were asked about how often they use the air conditioning during summer time, we got an average value for every day. But it is a known fact that August in Istanbul is much warmer than June or July (one must also consider the accumulation of thermal energy inside the house on top of the average daily temperatures), and therefore the use of air conditioning during August cannot be the same as June or July. It is therefore assumed that the air conditioning system would be used 50% more per day during August when compared to June or July, and that may be one of the reasons why the estimated consumption in August is almost 80% higher than those two months. But the actual consumption in August turned out to be more than twice the consumption in June or July, leading to a monthly error of 23.62%. This may have been caused by the excessive use of air conditioning systems beyond our estimations. Another possible explanation may be as follows: During the summer of 2015 when this analysis was performed, there were domestic water supply shortages in the Zekeriyakoy district, and many households had to rely on storage tanks for a few days. The storage tank for this particular house is underground, and it requires a powerful pump to supply water to the house. The electricity that could have been consumed by the pump was never considered in our estimations, and that can be another reason why there is a big difference between our estimations and the actual consumption. One might suggest adding a safety factor to the estimations to compensate for such unexpected occurrences, but in many months the estimations exceeded the actual consumption values and adding such a safety factor would only increase the error margins.

4.2. Battery sizing, net grid-dependency and feasibility analyses

Market analysis shows that the PV systems cost around $3,090 per kW (Chung, Davidson, Fu, Ardani, & Margolis, 2015), while BES system cost was found as $3,000 per single 6.4 kWh unit (Tesla, 2016). In other words, if the required capacity for the BES system is less than or equal to 6.4 kWh, then one unit should be enough and the initial cost would be $3,000. If the required capacity turns out to be between 6.4 and 12.8 kWh, there would be a need for two units and the initial cost would increase to $6,000, and so on. Household electricity price was taken as $0.14/kWh. In Table 4, the results of the battery capacity, net-grid dependency, and feasibility analyses are presented.

The results displayed in Table 4 show that while it is possible to reach very low net grid dependency values such as 9% when both the PV system and the BES system sizes are quite high, such investments are far from being feasible with payback periods approximately around

TABLE 3. Load estimation accuracy analysis

Month	Estimated Consumption (kWh)	Actual Consumption (kWh)	Relative Error (%)
January	663.939	684.635	-3.02%
February	595.149	584.19	+1.88%
March	581.701	529.706	+9.82%
April	569.962	512.462	+11.22%
May	472.311	430.976	+9.59%
June	543.907	499.762	+8.83%
July	558.683	512.663	+8.98%
August	926.971	1213.695	-23.62%
September	741.201	763.458	-2.92%
October	663.369	652.612	+1.65%
November	840.995	952.365	-11.69%
December	980.617	1101.402	-10.97%
OVERALL	8,138.805	8,437.926	**8.68%**

TABLE 4. Battery sizing, net grid-dependency and feasibility results.

PV System Size (kW)	Battery System Size (kWh)	Net Grid Dependency (%)	Total Initial Investment ($)	Annual Savings ($)	Payback Period (years)
1	6.4	85	6,090	170.92	35.6
2	6.4	70	9,180	341.83	26.9
4	6.4	46	15,360	615.29	25.0
4	12.8	42	18,360	660.87	27.8
8	6.4	29	27,720	809.00	34.3
8	12.8	20	30,720	911.55	33.7
10	6.4	25	33,900	854.58	39.7
10	12.8	16	36,900	957.12	38.6
10	19.2	13	39,900	991.31	40.2
13 (max.)	6.4	21	43,170	900.15	48.0
13 (max.)	12.8	12	46,170	1002.70	46.0
13 (max.)	19.2	9	49,170	1036.88	47.4

50 years. For different case studies where the local irradiation is higher and/or the household electricity consumption is lower, it might easily have been possible to reach 0% net grid dependency, i.e. a standalone system. However, it is practically impossible to achieve this goal in a feasible manner with the current market conditions and regulations in Turkey. With no local PV cell manufacturers, PV systems are still expensive in Turkey (Bavbek, 2015). But more importantly, the current regulations do not allow BES system owners to be involved in unlicensed energy generation schemes, which could have allowed the household owner to sell the excess electricity back to the grid at a minimum feed-in-tariff of $0.133 per kWh. This value could increase if the PV system is partially manufactured in Turkey – and indeed many PV system parts with the exception of the PV cell itself and the inverter can be manufactured locally today (Gözen, 2014). Therefore, the only option for a hybrid PV/BES system owner living in Turkey is to use all the electricity for themselves. Therefore, the current structure is regarded as a restrictive one and in order to promote the use of BES systems and increase the popularity of PV systems even further, it should be possible for BES system owners to be involved in unlicensed energy generation schemes.

5. CONCLUSION

A customer-oriented tool was designed to calculate the feasibility of a PV/BES combined system for a detached house. The electricity demand of the household throughout the year was estimated via performing a survey on the daily habits of the household as well as considering the changes in the need for lighting due to seasonal changes in the length of daylight times. No mathematical algorithm was used for the determination of the electricity demand. The overall error percentage between the estimated annual consumption and the actual consumption in the previous year was found to be 8.68%, showing that this study's approach is acceptable. The electricity supply coming from the PV system was calculated via "*http://pvwatts.nrel.gov/pvwatts.php*. The Microsoft Excel based tool prepared for this study calculates the required battery sizing, the net grid-dependency percentage for an entire year, and the feasibility of the PV/BES system based on the payback period. The tool was tested on a house in Istanbul, Turkey. The results, which obviously are not representative, showed that 0% net grid dependency is possible; however, it is not feasible due to the high cost of PV and BES systems, as well as the obstacles in the regulation system that prevents BES system owners from participating in unlicensed energy generation schemes such as feed-in-tariff for the excess electricity sold to the grid.

This particular tool was designed with the purpose of aiding house-owners to select the best possible system for their case, especially by using load estimation data which is as realistic as possible since it relies on hourly data rather than the electricity bill which only provides information on a monthly basis. A future study may involve the validation of methodology and preliminary results by an experimental, one or multi-year monitoring of a true, typical low-energy house in Turkey.

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