An Exploration of Design Options for Integrated Residential PV-ESS

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***Abstract*—The behind-the-meter integration of the distributed energy sources and the energy storage systems (ESSs) presents one of the key solutions for the 21st century energy and power challenges. A comprehensive design and development procedure, which integrates the energy management strategy, the power flow control and the sizing technique, into the system design can provide valuable insights and guidelines for the system operation and implementation. Most of the analyses and tools already presented in the literature do not consider a suitable design and development procedure for ESSs. In this paper, a novel design and development procedure suitable for integrated residential ESSs is presented. The procedure is composed of four stages: (i) Imports Parameters, (ii) Inputs Processing, (iii) Process Simulation and (iv) Design and Sizing Guide. The stages and the capabilities of the proposed design and development procedure are demonstrated through developed design algorithms based on the proposed procedure, looking at a real energy system in the UK.**

Keywords—integration of ESSs, design and development procedure, design of integrated residential PV-ESSs

I. INTRODUCTION

The increased penetration of distributed renewable energy sources (**RESs**) and especially photovoltaics (**PVs**) into the electricity generation mix has presented new challenges for the existing hierarchical, centrally controlled power grid, such as reliability issues, voltage instabilities, frequency harmonics, etc. [1]–[4]. At the residential level, the substantial reduction of the PV feed-in tariff subsidies across Europe [5] and the increase of the electricity prices [6], made the self-consumption of the domestic generated energy more attractive than feeding it into the power grid. The behind-the-meter integration of a residential PV and energy storage system (**ESS**) can address the aforementioned challenges through **i)** reduction of the electricity cost by offsetting peak tariffs, **ii)** increase of the self-consumption rates by consuming the generated energy domestically, **iii)** restriction of the voltage and frequency disturbances by reducing the injection of the generated power to the power grid and, **iv)** decrease of the grid reliability issues by increasing the self-sufficiency rate of the house. Although the combination of a residential roof-top PV system and an ESS could offer significant benefits for both the end-users and the power grid, many obstacles regarding the system design, implementation, public acceptance, policy support, financial support, investment costs, etc. need to be overcome, to become for being widely adopted [7], [8].

Traditionally, to suggest the most suitable energy flow and best operation of an energy system, a two level sequential approach was applied; first, the design process was followed and then, the control was deployed for its efficient operation and management [9]. Nowadays, it is highlighted that the two aforementioned stages (i) design and, ii) management and control) should not be seen individually but being integrated in one mathematical framework [10], which would provide the most beneficial operation and smooth function of each energy system [11]–[13]. Following a comprehensive, analytical and detailed design is important, as it can function as a catalyst that transforms technological innovation to system operation, through the valuable guidance and suitable framework for the actual project/system operation and implementation.

Up-to-now, little effort has been invested in developing suitable design procedures for the realisation of energy system-level goals regarding performance, predictability, feasibility, and profitability through appropriate design and development [14]–[16]. Three design and development procedures have found to be satisfactory for designing integrated residential ESSs [17]–[19]. A brief description is given below. [17] suggested a three step design procedure: **1)** define the purpose of the energy system, **2)** structure the system and **3)** quantify the external and internal assumptions regarding its operation. [20] followed a six-dimension classification: **a)** a top-down or bottom-up priority, **b)** time horizon, **c)** sectoral coverage, **d)** optimization or simulation techniques, **e)** level of aggregation, and **f)** geographic coverage, trading and leakage. The procedure presented by [19] includes: **I)** the applied mathematical techniques, **II)** the degree of the data intensiveness, **III)** the degree of model complexity and **IV)** the model flexibility. [21]–[23] quantified that a complete design and development procedure for ESSs needs to include the following factors/parameters: the serving purpose of the system, the location and hence, its restrictions and specifications, the power scale needed and the generation size (if fixed), the power delivery method, the available technologies for generation, transmission and distribution, the mode of operation, and the ownership.

This paper aims to address an existing design obstacle: propose a suitable design and development procedure for integrated residential ESSs (single houses and energy communities), which can define the feasibility/profitability of the examined/imported system by integrating the system management, control and sizing procedures into the system design, under valid assumptions of the electric component operation. This paper is organised as follows: Section II describes the outline of the proposed design and sizing procedure, Section III demonstrates the stages and the capabilities of the proposed design and development procedure through developed design algorithms based on the proposed procedure, looking at a real single house energy system, and Section IV summarises the main conclusions.

II. Outline of the Design and Development Procedure

The main goal of the procedure proposed in this study is to design economically profitable systems by defining their operational performance and energy management, under the most suitable power flow control and component sizing. This could be achieved through four blocks/stages as illustrated in Figure 1: **A.** Imported Parameters, **B.** Inputs Processing, **C.** Process Simulation and, **D.** Design and Size Guide.

A. Imported Parameters

The first stage of the design and development procedure is the Imported Parameters. During this stage, all the necessary information is gathered from the user, in order to structure the energy system under investigation.

Users' Power Profile: The electric loads (consumption power profile) and the generation data of the site (generation power profile) are required to be imported. If an energy community[1] is under investigation, multiple power profiles need to be imported. High sample resolution, i.e. one-minute instead of one-hour, results in a more accurate system representation (power domain) and hence, financial analysis.

Pricing: Pricing information is needed for implementing financial analysis. Pricing values could be: the electricity tariffs (electricity pricing schemes used by the end-users, i.e. flat or time-of-use tariff, community prices, i.e. tariff for discharging the communal ESS, etc.), the installation purchasing costs (components and installation costs), the incomes for exporting energy to the power grid, etc.

System Specifications: Necessary system specifications could be: the purpose of the system, the system limitations (i.e. available space, available resources, etc.), the ESS use ('self-consumption increase', 'peak independence', or their combination), the people/authority/entity that manage the energy community (when applicable), the system operational duration, etc.

Parameters under Investigation: Design parameters could concern: **i)** the ESS size (battery and power converter combination – energy and power rating), **ii)** the PV percentage for an energy community (percentage of PV installed power within the energy community), **iii)** the overnight charging control (this is included when the 'peak independence' ESS use is applied and hence, the battery charges from the off-peak electricity under a certain overnight charging control algorithm), etc. In addition, financial parameters, such as system revenues over the pre-defined operational period, financial benefits for the end-users when they act as members of an energy community rather than individually, etc., could be under investigation.

B. Inputs Processing

During the Inputs Processing stage, the energy system is structured according to the imported parameters as defined at the Imported Parameters stage, and the most suitable energy management and power flow control for the imported system are determined. Firstly, the consumption and generation power profiles need to be adjusted for each house; if an energy community is under investigation, the power profiles of the energy community houses need to be adjusted to the same time domain (i.e. same power sample resolution, considering the same chronological period, etc.). The most suitable models of the system components are selected according to the imported system specifications (i.e. battery chemistry, power converter efficiency, overnight charging algorithm, etc.). Then, the connections between the system's components are determined (i.e. ESS connected to the power grid for exporting the excess energy when the battery is full or when the power converter rating is lower than the required charging power).

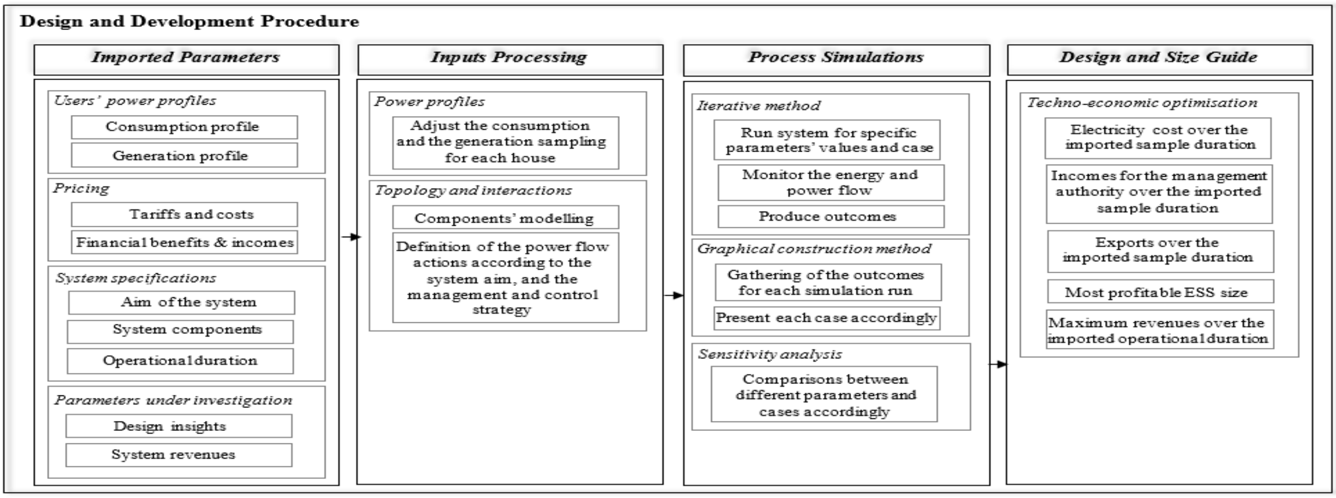

Figure 1: Outline of the proposed design and development procedure

[1] An energy community can be defined as a microgrid which connects nearby dwellings (consumers and prosumers) and individual or/and communal RESs or/and ESSs, and energy can be traded within its members and the power grid (if grid-connected).

After structuring the examined system, the optimal energy utilisation (suitable energy management) is defined based on the imported pricing, following the 'cheapest' energy source; the cheapest energy source is always the generated energy – self-consumption, whereas the most expensive is to purchase electricity from the power grid during the peak tariff periods. An appropriate and detailed energy management for energy communities with communal ESSs can be found in [24]. Based on the limitations imported during the Imported Parameters stage, and the operational limits of each electric component driven by the selected models (i.e. voltage and current limitations, power losses, power ratings, etc.), the power flow control is defined for the system aim and the system components' sizes. After the completion of this stage, the system is ready to be simulated by the design algorithms.

C. *Process Simulation*

The structured system of the previous stage (Inputs Processing) should be simulated by design algorithms, and run for different cases based on the parameters under investigation, as defined in the Imported Parameters stage. During the Process Simulation stage, the simulation results of each run for different examined parameters, are extracted by monitoring the power flow between the simulated system components and, the energy exchange and energy system balance. For instance, if the battery size was imported to be under investigation, the design algorithms should run for different battery sizes (except the battery capacity, the battery internal resistance need to be adjusted to the examined battery size), and the power flow between the system components will be monitored, as well as the system energies (such as export energy, off-peak purchased energy from the power grid, etc.).

By using the iterative method, the outcome of each investigated parameter can be quantified. Also, by using the graphical construction method, the outcome for N iterative runs (the number of iterative runs (N) is set according to the simulation goal) could be plotted in order for the user, to gain a better understanding of the influence of each parameter under investigation (battery capacity, power converter rating, overnight charging control algorithm, PV penetration percentage, etc.) on financial parameters (monthly electricity cost, peak and off-peak purchased energies, self-consumption rate, revenues for management authority/aggregators that supervise the operation of the energy community, etc.).

D. *Design and Size Guide*

The final stage of the design and development procedure developed is the Design and Size Guide. This stage presents the outcome of the parameters under investigation and provides design recommendations and sizing guidelines for the imported energy system. The outcome results are extracted through the engagement gained by the run of different scenarios and cases (i.e. comparison of different ES uses), by investigating various system components' control strategies (i.e. different battery utilisation) and/or by comparing different applications (i.e. single houses vs energy community). The outcome could be in graphic form (a set of figures, i.e. electricity cost for different battery and power converter sizes) and/or in text form (a set of numbers, i.e. optimal battery and power converter pair, and its revenues over a certain operational period). This final stage could be seen as the outcome results of a design tool or algorithms.

III. Demonstration of the Design and Development Procedure

For demonstrating the proposed procedure, design algorithms were developed in script language (Python) by following the stages of the design and development procedure. The design algorithms are able to simulate a variety of integrated residential ESSs, such as single houses with different ESS utilisations and energy communities with individual and/or communal ESSs. In this section, a real system is under investigation: a single house located in the UK with a 3.5kWp roof-top PV system installed, which is under the Economy7 electricity pricing scheme[2]. The case study illustrated in this section represents the capability of the design and developed procedure to suggest the most financially profitable ESS size (battery and power converter pair) for a single house with an existing roof-top PV system, based on extensive financial analysis.

A. *Imported Parameters*

Users' Power Profile: Simultaneous power consumption and generation profiles with 5-minute sample resolution were imported in the design algorithms. Figure 2 presents the imported power profiles for one week of each season. More details about the imported dataset can be found in [25].

Pricing: The Economy7 pricing scheme was applied, with the off-peak tariff being 4 times lower than the peak tariff. The exported benefit was taken to be half the off-peak tariff. The imported costs: **i)** installation cost: £300, **ii)** battery capital cost (3 pricing scenarios were examined for the battery): 5p/Wh, 10p/Wh and 20p/Wh, **iii)** converter cost (2 pricing scenarios): 30p/W and 50p/W and, **iv)** PV cost: 70p/W.

System Specifications: With the installation of the ESS, the house aims **i)** the increase of the self-consumption by storing excess PV energy and **ii)** decrease of the peak dependency via charging the battery overnight during the off-peak period. The components of the examined system are: the house (power consumption profile), the ESS (battery and power converter), the PV system (power generation profile), and the power grid. The imported operational duration was 10years, which could coincide with the interval where major refurbishment (i.e. battery replacement) may be undertaken.

Parameters under Investigation: The design parameters under investigation are: the battery size, the power converter rating, the PV size and the overnight charging control algorithm. The financial parameters are: the monthly electricity cost and the system revenues at the end of the operational duration.

B. *Inputs processing*

The system was structured based on the imported components. The schematic of the structured system can be found in the Figure 3. The design algorithms made use of already developed ESS models - the description of the models used (battery, power converter, overnight charging control algorithms etc.), can be found in [26], and the energy management and power flow control applied in [27].

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[2] Economy7 is the first and most popular time-of-use tariff in UK [28]. It can be defined as an incentive from the electricity utilities to encourage consumers shift their electricity consumption during off-peak hours. An Economy7 meter records the electricity usage on two rates: from 00:00-07:00 an off-peak rate is applied, whereas, for the rest hours of the day, a peak tariff is used.

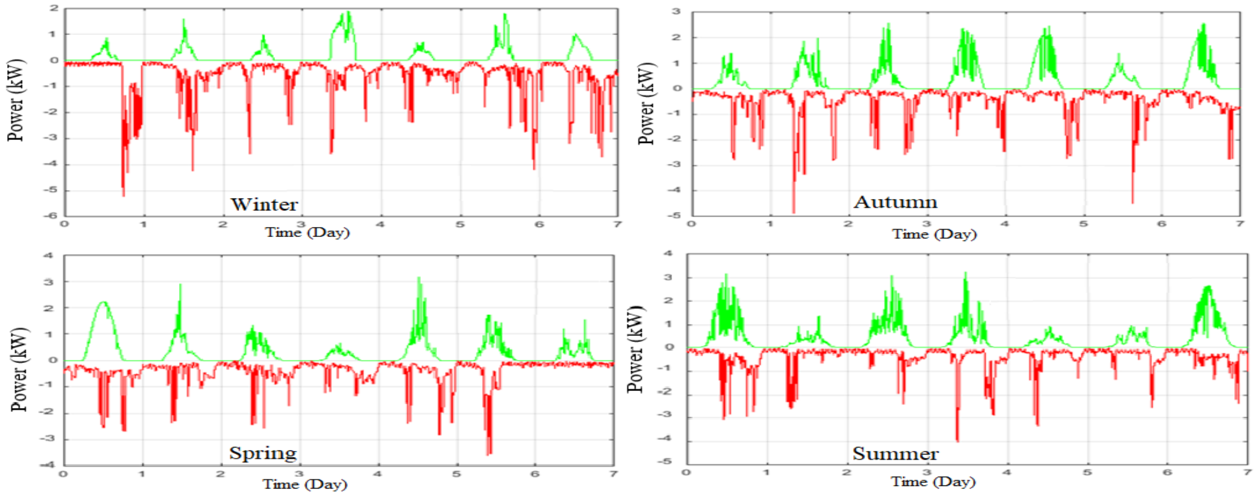

Figure 2: Imported power profile - one week of each season (green: PV generation, red: power consumption)

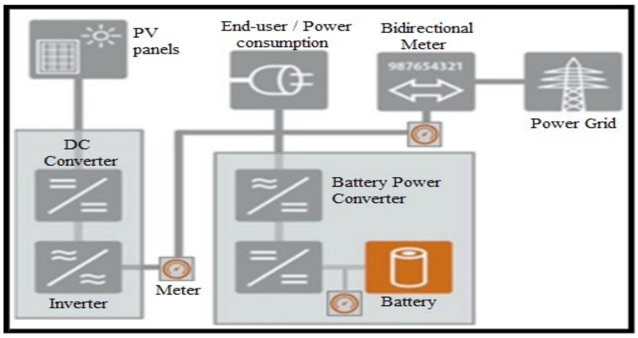

Figure 3: Schematic representation of the structured system

Throughout the system operation, the electric and system limitations are satisfied, as defined by the power flow control and the energy management technique followed. Indicatively, Figure 4 illustrates the battery charging patterns for the four weeks illustrated in Figure 2. At the beginning of each day, if the battery capacity is lower than the pre-defined overnight charging level (star SOC percentage of the Figure 4), the battery charges up to the overnight charging level. At the end of the off-peak period, the charging pattern follows the power profile; if the generation is higher than the consumption, the excess energy charges the battery (if not full), otherwise, the deficit energy is taken from the battery through the discharging process (if not empty).

C. Process simulation

The design algorithms run for different parameters under investigation (defined during the Imported Parameters stage) and the output values of the financial parameters under investigation were captured for each simulation run. Figure 5 presents the average monthly electricity cost (it was defined as a financial parameter under investigation during the Imported Parameters stage), for the 3 examined design parameters under investigation: **i)** battery capacity, **ii)** PV size, and **iii)** overnight charging control algorithm. The detailed description of the overnight charging control algorithms considered can be found in [25]. Some generic notes from Figure 5 could be that, a larger PV and battery size provide a lower electricity cost to the end-users. However, above a certain battery size (for larger PV sizes, the threshold battery size decreases), there is no significant reduction of the electricity cost and a further increase of the battery size will not provide any financial benefit to the end-users. On the other hand, a more intelligent overnight control algorithm lowers

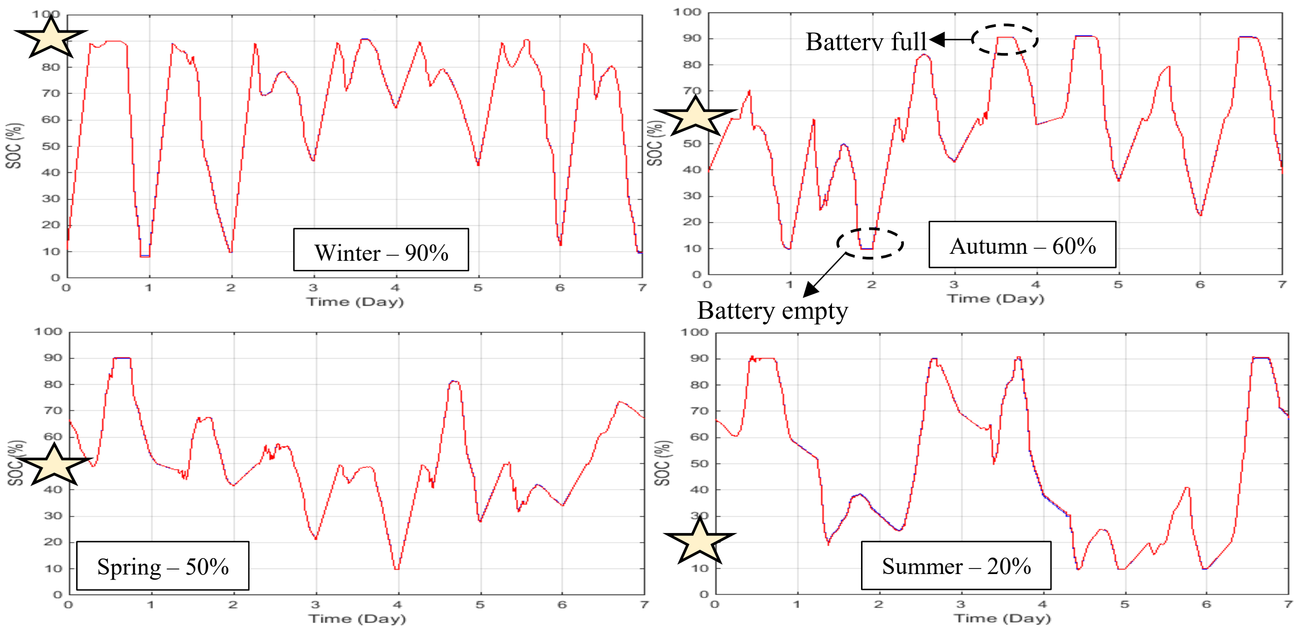

Figure 4: Battery charging patterns for the weeks depicted in Figure 2 (battery size: 7kWh, converter rating: 2.5kW, PV: 3.5kWp, overnight control: seasonal

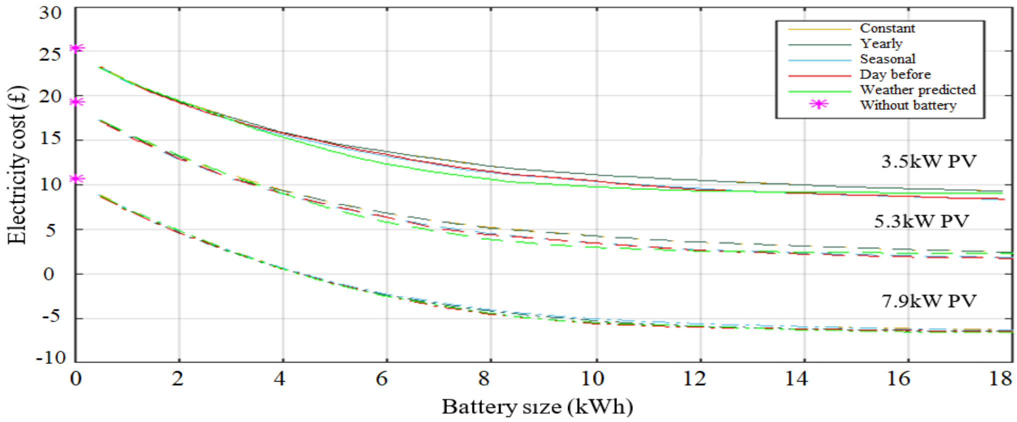

Figure 5: Average monthly electricity cost for different PV sizes, battery capacities and overnight charging control algorithms

the electricity cost for a small or medium PV installation size (≤5kW) and when there is sufficient energy storage available. Furthermore, more PV installed power (when it is possible) can be substituted for more installed battery capacity. Overall, from Figure 5, it can be concluded that simply oversizing the battery and PV will not result to a significant reduction of the house electricity cost. Similarly, installing an intelligent overnight charging control algorithm without considering the battery and the PV size of the specific system might result to negligible financial benefits.

D. Design and size guide

This stage provides the outcome of the design algorithms to the user for the imported system and the parameters under investigation. A demonstration of this stage could be seen in Figure 6, which illustrates the financial benefits over the imported operational period (financial parameter under investigation), for different battery sizes, power converter ratings and pricing scenarios (design parameters under investigation). Four sizes of the power converter interfacing with the battery were chosen to be presented here, ranging from full power 5kW able to supply all power peaks recorded in the load power profile but being characterised by a high cost and lower efficiency when operating at the average power level, down to 0.3kW which would be very cheap and deliver the refrigerator power needs but will not be able to process powers that were exceeding the average load power level.

All the revenue curves shown in Figure 6 have a maximum point at the most profitable battery size. However, due to the high purchasing costs typical for ESSs, the revenues are mostly negative over the 10-year operational duration. In particular, despite the fact that a larger ESS size provides a lower electricity cost to the end-user (as it was shown in Figure 5), its financial benefit on the electricity cost does not compensate for its high purchasing cost. A proof of this statement is the negative revenues for all the examined battery sizes of Figures 6.D&E, which represent the revenues for the 2.7kW and 5kW power converter rating respectively. For this specific system, the most profitable ESS size was found to be the 8kWh battery and the 0.9kW power converter for the 3.5kW PV, as over the 10-year operational period, this combination provides the highest financial revenues to the end-user (approx. £480 – star point of Figure 6.B).

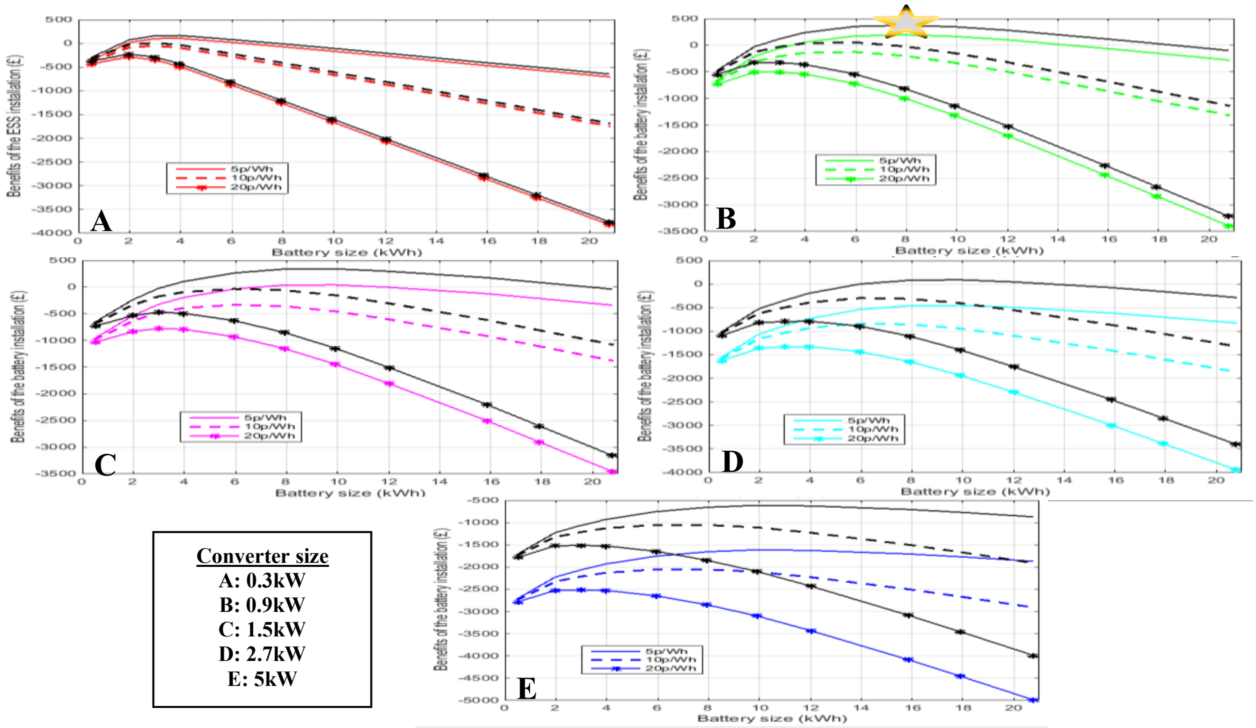

Figure 6: Financial benefits (revenues minus system costs) for the imported system operational duration – star: most beneficial battery and converter size

IV. CONCLUSIONS

The benefits of integrating behind-the-meter renewable energy sources and energy storage systems (**ESSs**) are widely recognised, as they can offer: **i**) reduction of the electricity cost by offsetting peak tariffs, **ii**) increase of the self-consumption rates by consuming the generated energy domestically, **iii**) restriction of the voltage and frequency disturbances by reducing the injection of the generated power to the power grid and, **iv**) decrease of the grid reliability issues and the house electricity prices' dependency by increasing the self-sufficiency rate of the house. However, a plethora of obstacles restricts the wider implementation of integrated residential ESSs. This paper focuses on a design obstacle: the lack of a suitable design and development procedure that can define the feasibility/profitability of the examined/imported system by integrating the system energy management, power flow control and sizing procedures into the system design, under valid assumptions of the electric component operation.

The outline of the proposed design and development procedure is described: the **Import Parameters** stage collects the necessary information for the system under investigation, the **Inputs Processing** stage converts the imported parameters to useful values for the upcoming analysis, the **Process Simulations** stage monitors the system operation for different parameters under investigation, and the **Design and Size Guide** stage provides the outcome of the undertaken analysis to the user, in the form of design and sizing guidelines. Design algorithms, which followed the aforementioned stages, were used to demonstrate the stages, and to illustrate the capabilities, of the proposed design and development procedure, looking at a real energy system.

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