Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 118 (2015) 58 – 71

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

'Buildings as Power Stations': an energy simulation tool for housing

Ester Coma*, Prof. Phil Jones

Welsh Scool of Architecture, Cardiff University. Bute Bldg, King Edward VII Avenue, Cardiff CF10 3NB, United Kingdom

Abstract

The concept of 'Buildings as Power Stations' (BAPS) represents a major shift in the way that electricity is generated, stored and used. Buildings are no longer simply consumers of electricity, but active players in the electric power system. Reducing energy demand to 'PassivHaus' levels of performance and the full integration of photovoltaic modules and wind turbines with buildings is itself a challenge to architects and house builders. Combining these with the sizing of the batteries for electrical storage through a 'systems' approach, optimizing performance and cost across reduced energy demand, renewable supply and storage, needs a suitable 'user-friendly' modeling framework, which is currently not generally available to designers.

The new BAPS tool presented in this paper assesses if a building has the potential to become a 'Power Station' by analyzing the energy generated from building-integrated renewables (including, solar and wind), the effect of using electrical energy storage systems and the impact of introducing demand reduction technologies. The BAPS tool enables an architect, via an easy to understand user interface, to assess the potential for renewable energies and battery storage and provides guidance on the selection of the battery system for a range of residential applications.

The paper describes how the tool has been used in the design of the prototype 'near zero' carbon SOLCER House, currently under construction in South Wales, UK. The tool has been used to evaluate the building energy system, including the sizing of solar PV panels and the li-ion battery storage, in the context of the buildings reduced demand for electricity, through the use of LED lighting and high efficiency appliances. The optimum mix of renewable energy and grid based energy supply is presented for the SOLCER House.

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015

Keywords: electrical energy storage; sizing systems; integrated energy systems; hybrid energy systems; simulation tool; bottom-up approach; buildings as power stations

* Corresponding author. Tel.: +44 (0) 29 2087 0463; fax: +44 (0) 29 2087 4623
E-mail address: ComaE@cardiff.ac.uk

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015
doi:10.1016/j.proeng.2015.08.404

1. Introduction

The concept of 'Buildings as Power Stations' represents a major shift in the way that energy is generated, stored and used in a building. It is the idea that every building, however small, can play an active role in the electric power system rather than simply being a passive consumer, with renewable energy generation integrated into the building design.

Some non-domestic buildings are already being designed to function like small-scale power stations, with multi-megawatt photovoltaic power stations integrated in their roofs and excess generation capacity feeding in to the UK National Grid as Short Term Operating Reserve (STOR). However, that is not often the case for domestic buildings. This paper presents a 'bottom-up' approach to the residential sector energy challenge through a building energy systems approach for electrical power, incorporating reduced energy demand, renewable energy supply and energy storage. The aim of this proposed bottom-up approach is first to design an individual building as a power station, in this case an affordable house, that can become autonomous or near autonomous in its energy use with the power supply from the grid used only as a backup when the renewable energy storage system has been depleted. Generally, full energy autonomy is too costly, especially in terms of energy storage, therefore, an optimization process is needed to ensure the most efficient and effective balance is achieved between building integrated renewables and grid-based electricity generation. At this point in time, full energy autonomy would only be used for houses in off-grid situations. This paper described software developed to enable this process and a case study building to which it has been applied.

1.1. Research scope and focus

The scope of the research is the housing sector and its energy use, which in the UK accounts for around 30% of the total energy demand and 27% of the total CO_2 emissions [1]. This paper focuses on the new housing sector, by proposing a model of a flexible house prototype with integrated renewable energy systems. However, these systems have been carefully designed taking into account the existing housing stock in the UK, so they could also be implemented as a retrofit solution in future research projects.

In order to design such a system, a tool named BAPS has been developed for simulating any domestic-scale energy system, combining energy generation, storage and use (illustrated in Fig. 1). Initially, energy from renewable energy systems will be used directly to cover the demand. Using the renewable energy directly in the building, rather than exporting and importing it to the grid, could avoid grid overvoltage, reduce capital cost, increase reliability and improve system's efficiency. When there is an excess of renewable energy generation, this will be stored in the building's energy storage system for later use, which in this case is a battery system. Oppositely, when generation and storage cannot cover the demand, electricity will be imported from the grid. The proposed BAPS tool initially looks at individual buildings, in this case a dwelling. But in future research, it could look at the larger scale and consequently have an 'upward' impact on the community and urban scale energy system.

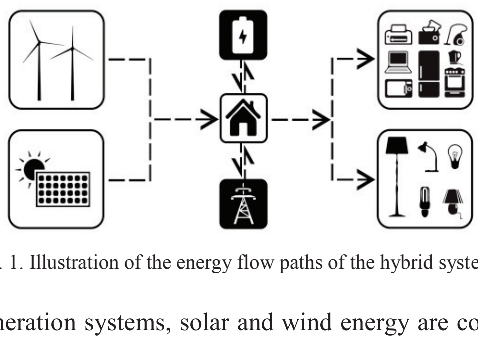

Fig. 1. Illustration of the energy flow paths of the hybrid system

Regarding renewable energy generation systems, solar and wind energy are considered the most appropriate due to their growing acceptance in the UK. Since the sun and wind often occur at different times, a combination of both sources provides a more reliable and constant power supply [2] [3]. Moreover, because they are constantly changing in nature, being weather dependent, the energy storage can be designed to allow an optimal balance between the available energy supply and the demand loads throughout the year [4]. For solar, the 'Buildings as Power Stations' approach is to fully incorporate the renewable energy generation system as an integrated component of the building envelope. In new buildings this also reduces costs, due to the solar PV system also acting as the roof (or wall) envelope element, compared to the more traditional approach of 'bolting on' a solar PV system to a traditional roof (or wall). For wind, the integration of renewable energy generation in the building design is challenging, so the role of these systems is probably more appropriate on the larger scale, for example, community and city scale, which is more a topic that should be analyzed in future research.

Eventually, this research aims to assess the potential of the new UK's households to become 'Buildings as Power Stations', hence to be active energy generators rather than passive energy consumers. The BAPS assessment tool, with its user-friendly interface, has the potential to help turn any UK household into a power supply plant by calculating the appropriate size of the supply and storage systems that will lead to maximizing the use of renewable energy and minimize the amount and cost of electricity purchased from the grid. The aim is then to reduce the dependency of UK dwellings on the grid; this will not only reduce demand peaks of the grid but also will contribute to reducing potential overload on the grid. The extent to which such systems act as a reducer of grid peak demand or near autonomous energy supply with grid back-up, will be determined by the size of renewable energy system and the storage capacity, in the context of the building's reduced energy demand.

1.2. Research context

It is crucial to reduce our dependency and consumption of fuels, not only in relation to global issues of climate change and energy supply, but also as part of future sustainable living for society in general. For that reason, it is essential to ensure that the housing sector plays its role in helping to reach the UK government's targets of a 34% reduction in greenhouse gas emissions by 2020; a 50% by the mid-2020s; and an ambitious 80% by 2050 [5].

In order to achieve these targets, the UK has to address these problems through integrated policy and market mechanisms, especially in the energy and built environment sectors. Therefore, this paper aims to have an impact on the UK's households by applying a low carbon alternative to the current concept of housing, and demonstrating that it can be achieved through affordable solutions that can be implemented with the use of current technology and skills.

The research model development work presented on this paper has focused on the design and construction of a 'near zero' carbon house prototype, the SOLCER House (Figure 2). The house has been designed to a PassivHaus level of energy demand, incorporating fully integrated renewable thermal and electrical energy supply, and thermal and electrical energy storage. This house is currently under construction in Wales and is due to be completed in February 2015. The overall research program includes both the development of the BAPS tool and the design and construction of the prototype SOLCER House. This combines a theoretical approach in terms of design and modeling of the building and its systems, with more practice based research of implementing the BAPs tool to size the energy system for a house in the real world. Characteristics such as flexibility, affordability, viability or replicability, and demonstrating performance in use, are essential in order to ensure that the designed prototype SOLCER House can become a real alternative in the UK housing market and attract the interest of the public (builders, local authorities, RSL, individual users, etc.).

Fig. 2. SOLCER House. Left – South facing elevation with integrated Transpired Solar Collectors and Photovoltaic roof. Center – North elevation, main access. Right – Section of the house.

2. Methodology

The ‘Buildings as Power Stations’ goal presents a challenge for architects, who now have a decisive role to move forward the ‘Low Carbon Housing’ agenda if they are to play a leadership role on a building project team [6]. Traditionally architects used sketches, renderings and pattern books supplemented with axonometric and perspective drawings, written and diagrammatic specifications, photographs and small-scale models. This was a conventional architectural design methodology, which focused on building’s space and form.

Contrarily, this paper proposes a ‘performance-driven’ [7] architectural design, which takes a holistic approach towards energy and thermal performances of buildings while ensuring that the use and aesthetic of the design are not dismissed. In recent years mathematical models, energy performance simulation techniques, as well as computer-aided design and drafting systems have been used. However, architects often find them impractical and incompatible with their knowledge base and design approach [8]. Therefore, it is necessary to develop an effective method to conduct ‘performance-driven’ design and systems optimization from the perspective of architects. Hence, the SOLCER house prototype, together with the BAPS tool, is proposed as an example solution. BAPS has been developed as a quick and easy to understand tool, which can be used in the early stages of the project, to design or even refurbish dwellings through a legible ‘performance-driven’ approach.

2.1. BAPS Tool: Inputs

BAPS Tool is operated through a simple Excel based user interface, which outputs the results of the system’s simulation in an easy to understand reporting format. The calculation process starts in ‘Step 1’ (see Fig. 3) by defining the characteristics of the energy demand, supply and storage options.

Figure 3. Screenshot of the BAPS Tool – Step 1

BAPS aims to include flexibility in the modelling process in order to model almost any household in the UK. For this reason, variations are allowed on the following aspects.

2.1.1. Demand

Energy use in dwellings is driven by occupants' needs, therefore it depends on the level of services required in relation to the type of home and its water heating system, lighting and appliances. Moreover, energy use in UK households is highly influenced by both the size of the dwelling and the number of people living in it [9]. Accordingly, the following factors in Table 1 have been considered in order to model the energy demand of a home using the BAPS tool:

Table 1. Demand variation parameters.

		Variations	Factor
(1) Occupancy			
	Family size [10]	1 Adult	$F1_{FS}$ = 1.00
		1 Adult + 1 Child	1.75
		1 Adult + 2 Child	2.50
		2 Adults	2.00
		2 Adults + 1 Child	2.75
		2 Adults + 2 Child	3.50
		2 Adults + 3 Child	4.25
		2 Adults + 4 Child	5.00
	Environmental Attitude [10]	Pro-Active	$F1_{EA}$ = 0.87
		Non-active	1.00
(2) Building			
	Building Size	50 sqm	$F2_{BS}$ = 50
		60 sqm	60
		70 sqm	70
		80 sqm	80
		90 sqm	90
		100 sqm	100
		110 sqm	110
		120 sqm	120
	Building Type [10]	Terraced house – mid	$F2_{BT}$ = 0.725
		Terraced house – end	0.898
		Semi-detached house	1.004
		Detached house	1.083
		Bungalow	1.008
		Flat	0.738
(3) Demand			
	Demand Type	Option 1	Lighting Computers Portable Units
		Option 2 = Option 1 +	Fridge/Freezer TVs/Audiovisuals Small Appliances
		Option 3 = Option 2 +	Space/Water Heating Cooking Washing

2.1.2. Supply

Building integrated renewables are restricted to what energy sources are available on site and what can be fitted in, on, or around the building. Hence it is crucial to minimize the building's energy demand before considering or designing a renewable system. Although solar and wind energy are freely available everywhere and environmental friendly, renewable energy systems are often perceived to be expensive, thus it is important to optimize their size and integrate them into the building construction to save on overall construction costs.

The factors in Table 2 have been considered in order to model the renewable supply with the BAPS Tool.

Table 2. Supply variation parameters.

	Variations	**Factor**
(1) Location		
England	North East	Newcastle upon Tyne
		Sunderland
	North West	Blackburn
		Blackpool
		Liverpool
		Manchester
	Yorkshire	Bradford
		Leeds
		Sheffield
		York
	East Midlands	Derby
		Leicester
		Northampton
		Nottingham
	West Midlands	Birmingham
		Coventry
		Stoke-on-Trent
		Wolver Hampton
	East England	Cambridge
		Ipswich
		Luton
		Norwich
		Southend-On-Sea
	South East	Brighton
		Milton Keynes
		Oxford
		Portsmouth
		Reading
	South West	Bournemouth
		Bristol
		Exeter
		Gloucester
		Plymouth
	London	London
		Sutton
Wales	South Wales	Cardiff
		Swansea
		Newport
	North Wales	Wrexham
Scotland	Lothian	Edinburgh
	Strathclyde	Glasgow
	Grampian	Aberdeen
	Central	Dundee
Ireland	Northern Ireland	Belfast
(2) Building		
Roof Area	10 to 75 sqm	
Roof Angle	10° to 45°	
(3) Solar Energy		
PV Orientation	S, SW, W, E, SE	
PV Efficiency	8 to 23%	
(3) Wind Energy		
Feasibility	Yes or No	
Size Wind Turbine (radius)	1.5 to 4.5 m	

2.1.3. Storage

The BAPS tool needs to incorporate energy storage systems in order to ensure the use of electricity at times when the renewable energy systems are not generating power, i.e., no sun or wind. Lead-acid batteries and lithium-ion batteries are the most commonly used storage system at the moment, and correctly sizing them is crucial in order to achieve a well-designed energy system as proposed in this paper.

There are many factors affecting battery bank sizing, and they all have been considered in the calculation procedure used by the BAPS tool. The main conditions are:

(1) Size – Days of autonomy and depth of discharge.
(2) Typology – Battery type, system's voltage and ambient temperature.

One of the conditions for sizing batteries are the days of autonomy, i.e., the number of days of battery back-up that the storage system can provide. Another important factor is the depth of discharge (DoD), which is the limit of energy consumed from the battery, expressed as a percentage of the total capacity. Fully discharging batteries can reduce their operation lifetime considerably. For example, the DoD for lead-acid batteries should be no greater than 50%, while for li-ion batteries it can be up to 80%. The third aspect to consider is the ambient temperature, since low temperatures reduce battery capacity, while high temperatures shorten battery life. Finally, the voltage of the whole energy supply system needs to be determined; this is usually 230V in the UK.

2.2. BAPS Tool: Calculation Engine

The proposed BAPS tool assesses the energy generated from renewable energy systems, the effect of using battery storage systems, and the impact of demand reduction technologies. The BAPS calculation process updates automatically, hence any change on the systems' characteristics chosen in 'Step 1' has an instant impact on the results, which are immediately shown in parallel screens. The calculations are as follows:

2.2.1. Demand

The energy demand profile is set up through the user defining the level of occupancy, the occupant's environmental attitude (pro-active; non-active), the number of appliances to be connected to the battery system, and the building description (floor area; typology). The data used in the calculations to determine energy demand profile then extrapolates from the following information:

(1) Data Considerations:
- Average Occupancy of UK Households – In 2011, the average household size in the UK was 2.3 people per household, compared to 2.4 in 2001 [11].
- Average Size of UK Households – The average home in the UK is 85 m^2 and has 5.2 rooms [12].
- Average Daily Demand of UK Households – Average daily electrical use, which is based on the average electricity use profiles from 250 households, monitored over 12 months using meters on total electricity use and most appliances) [13]. Accordingly, appliances are grouped:
  - Option 1: lighting, computers and portable units;
  - Option 2: option 1 and fridge/freezer, TVs/audiovisuals and small appliances;
  - Option 3: option 2 and space/water heating, cooking and washing appliances.

(2) Calculations per each group of appliances (i):
- Average Hourly Demand ($D_{AH\text{-}i}$) – From Table 3.11 in ECUK (2013) [13].
- Occupancy Factor (F_O) – Based on Table 2 in 'Powering the Nation' [10].
- Size Factor (F_S) – Floor area of the household in m2.
- Environmental Factor (F_E) – 1 (if not active) and 0.85 (if active) [13].

(3) Hourly demand per each group of appliances ($D_{H\text{-}i}$).

$$D_{H\text{-}i} = D_{AH\text{-}i} \bullet F_O \bullet F_S \bullet F_E \quad (1)$$

2.2.2. Supply

The user sets up the renewable energy supply options for a specific roof area, system size and building location (currently restricted to the UK), based on the following information:

(1) Solar Power:
- Hourly Solar Global Radiation ($S_{H\text{-global}}$) – From the weather data of each location, obtained from Meteonorm Software [14] database.
- Hourly Solar Irradiation falling on the roof ($S_{H\text{-roof}}$) – 40 house prototypes were modelled in HTB2 Software [15], considering a range of roof variations (8 angles and 5 orientations) for each location.
- PV Efficiency Factor (F_{Eff}) – Efficiency is the percentage of incident solar power which is converted into electricity by the solar cell.
- Hourly supply from solar energy ($S_{D\text{-solar}}$):

$$S_{H\text{-solar}} = S_{H\text{-roof}} \cdot F_{Eff} \tag{2}$$

(2) Wind Power:
- Hourly Wind Speed (V_H) – From the weather data of each location, obtained from Meteonorm Software [14] database.
- Cut-in and cut-out speeds – From typical wind turbine specifications.
- Hourly supply from wind energy ($S_{D\text{-wind}}$):

$$S_{H\text{-wind}} = \tfrac{1}{2} \cdot \rho \cdot (\Pi \cdot r^2) \cdot (V_H)^3 \cdot C_P \tag{3}$$

Where, ρ is the air density, $(\Pi \cdot r^2)$ is the swept area of the turbine blades, V_H is the hourly wind speed and C_P is the Betz limit with a value of 0.4 [16].

The calculations associated with renewable energy systems assume no shading of PV solar panels and no turbulence associate with the wind. In practice, the latter may be particularly an issue depending on the siting of the wind turbine in the context of surrounding buildings and their impact on wind conditions.

2.2.3. Storage

In selecting the energy storage system, the user may select the level of energy autonomy required and its operating conditions, using the following information:

(1) Electrical load balance calculations:
- Hourly energy balance between supply and demand.
- Hourly energy difference between demand and supply, energy excess when electricity can be stored into the energy storage system; or energy deficit, when electricity will be supplied from batteries or, in 'back-up' mode, provided from the grid.

(2) Sizing of the battery system:
- Battery bank's storage capacity (I_{BB}) in Ah:

$$I_{BB} = (D_D \cdot A_d \cdot T_a) / (DoD \cdot V_s) \tag{4}$$

- Where, D_D is the daily demand to be covered with batteries, A_d are the days of autonomy, DoD is the depth of discharge, T_a is the ambient temperature and V_s is the system's voltage.
- The number of batteries needed (N_B) will depend on the model and its storage capacity (I_B).

$$N_B = I_{BB} / I_B \tag{5}$$

(3) Yearly performance of the battery system.
- Battery bank's electrical supply capacity (P_{BB}) in Wh for a specific voltage:

$$P_{BB} = I_{BB} \cdot V_s \tag{6}$$

- Consideration 1: The initial state of the battery bank is fully charged, hence its power is P_{BB}.
- Consideration 2: Batteries are charged from renewable energy only when there is surplus of electricity and batteries are still not full, and are discharged to supply the demand loads only when the demand cannot be met by the renewable energy supply and the batteries are still not empty.
- Hourly energy performance of the battery system is calculated by adding the energy excess or subtracting the energy deficit from the existing P_{BB}.

3. Results

By using BAPS tool, assuming that appropriate information is at hand, an entire ‘Building as Power Station’ assessment study can be achieved in less than 5 minutes. The outputs of the calculation are then presented in 3 different screens, which represent supply, demand and storage respectively; and a final sizing report.

3.1. BAPS Tool: Outputs.

The BAPS tool allows the user to instantly see how changes on the systems’ characteristics have an impact on the output results. Therefore, BAPS not only provides a final solution but also allows the user to compare it with different design options and sizing variations. What differentiates BAPS from existing hybrid energy systems software tools, is the ease at which the user can consider the implication of introducing battery energy storage area into the system. In account of that, size, dimensions and weight of the battery system are known in the early design stage so that architects can enable them to be integrated within the buildings.

3.1.1. Step 2: Demand

Demand profiles are shown by type of appliances, allowing the user to see which typology consumes more or when the peaks of consumption occur. Graphs are presented on a daily, monthly and yearly output as respectively shown in graphs 1, 2 and 3 in Fig. 4. On the left hand side of each of these graphs, the energy demand from lighting, all appliances and space/water heating, is shown with number figures as well as on a pie chart.

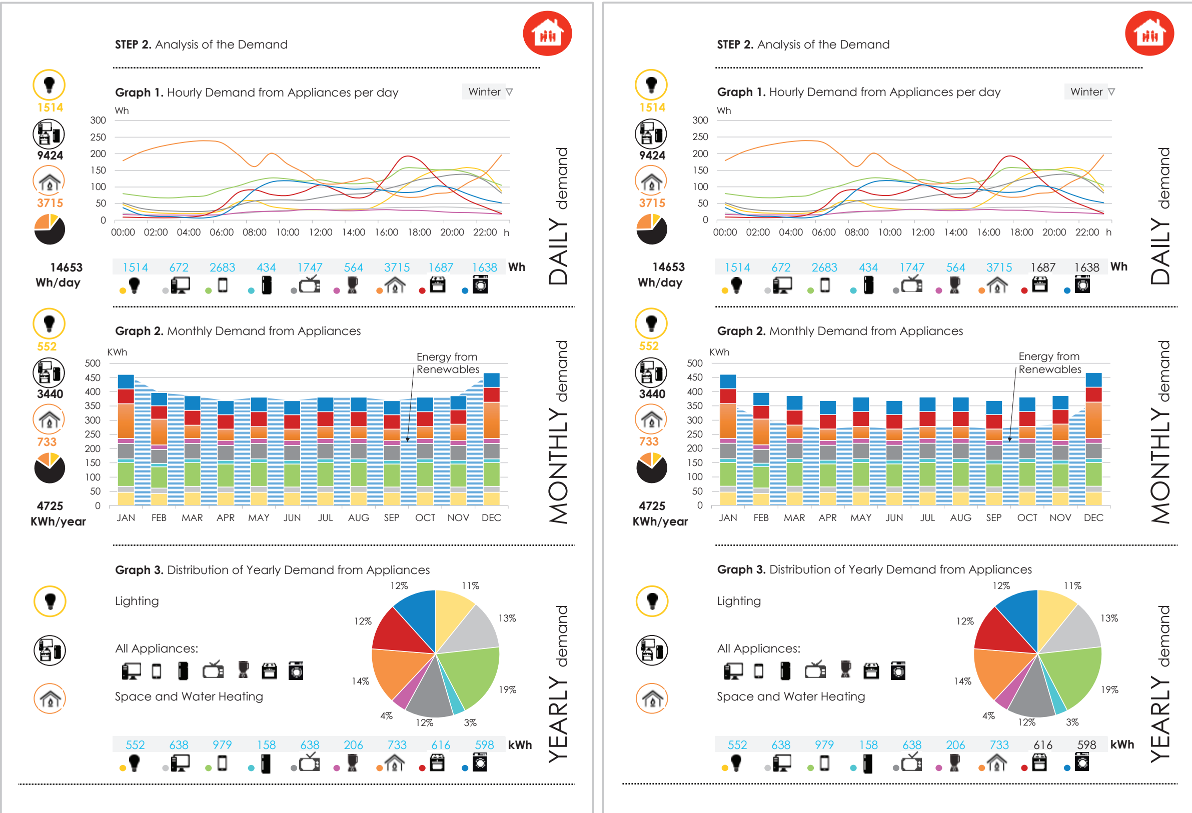

Figure 4. Screenshot of the BAPS Tool – ‘Step 2 - Demand’. Left – Demand profiles for SOLCER House defined previously in Step 1 (see Fig. 2) with demand type ‘Option 3’. Right – The same but with demand type ‘Option 2’.

Graph 1 shows the hourly demand profile of each appliance type over one typical day in spring, summer, autumn or winter. Also the table below presents the amount of daily energy demand of each type of appliance and it indicates if they are connected to the renewables/battery system (numbers in blue) or directly connected to the grid (numbers in black). In graph 2, a bar chart shows the monthly profile of energy use for each type of appliance while a blue profile on the background outputs de value of energy to be covered with renewables/battery system. Finally, the last graph 3, gives the percentage and the amount of energy demand that each appliance type consumes.

3.1.2. Step 3: Supply

Supply profiles are separated by type of energy source, thus solar and wind power are shown in yellow and blue respectively. They are presented on a daily and monthly basis and as a PV size optimization output (see Fig. 5).

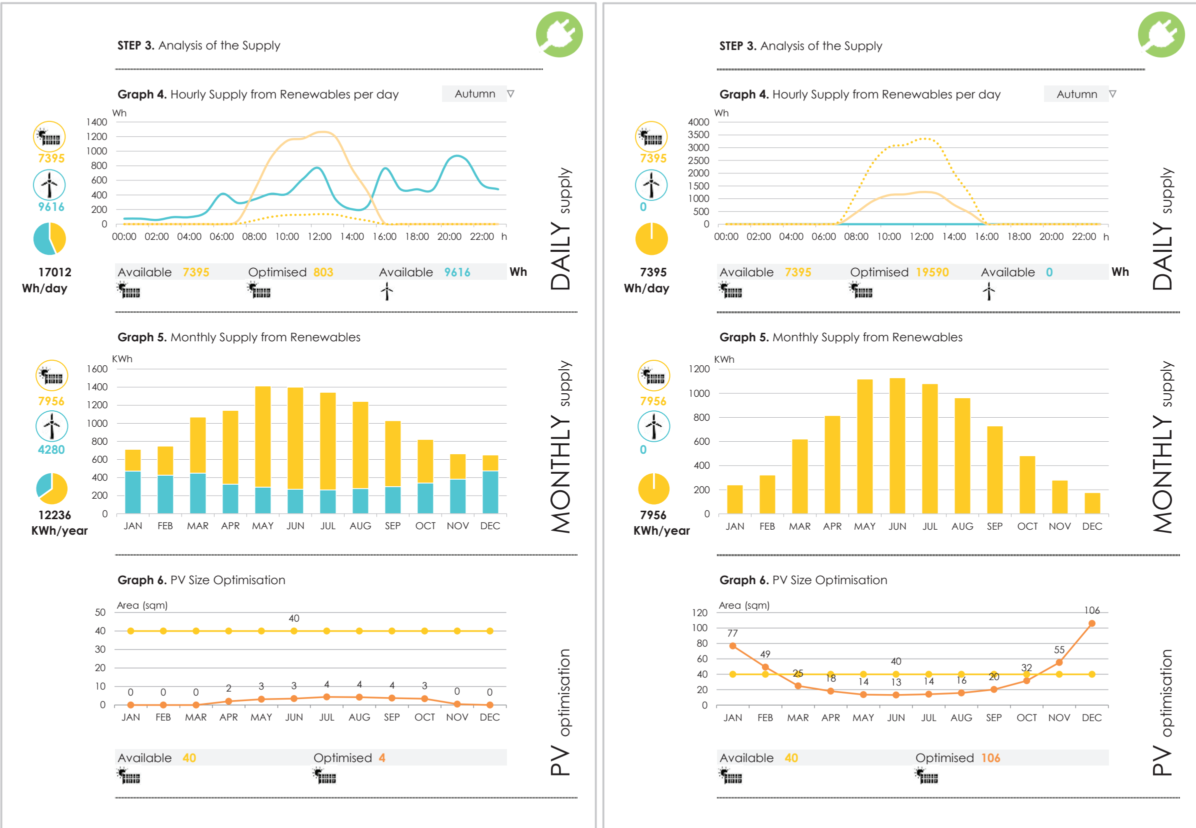

Figure 5. Screenshot of the BAPS Tool – 'Step 3 - Supply'. Left – Solar and wind power generation for SOLCER House case study. Right – Solar only. In the SOLCER House case study only building integrated PV was used, wind being considered too difficult to integrate into the building design.

Graph 4 shows the hourly supply profile of both solar and wind power over one typical day in spring, summer, autumn or winter. Also, it proposes an optimized profile of solar supply (dotted line). In graph 5, the bar chart shows the seasonal variations of solar and wind energy, and also how the combination of both energy sources can contribute to the seasonal balance. Finally, graph 6 indicates an optimized area of PV panels and compares this given value with the available roof area.

3.1.3. Step 4: Storage

Demand and supply profiles are compared to find their energy balance, in other words, to see whether there is more energy being generated by renewable systems or consumed by the householders. Results are presented daily, monthly and annually (see Fig. 6).

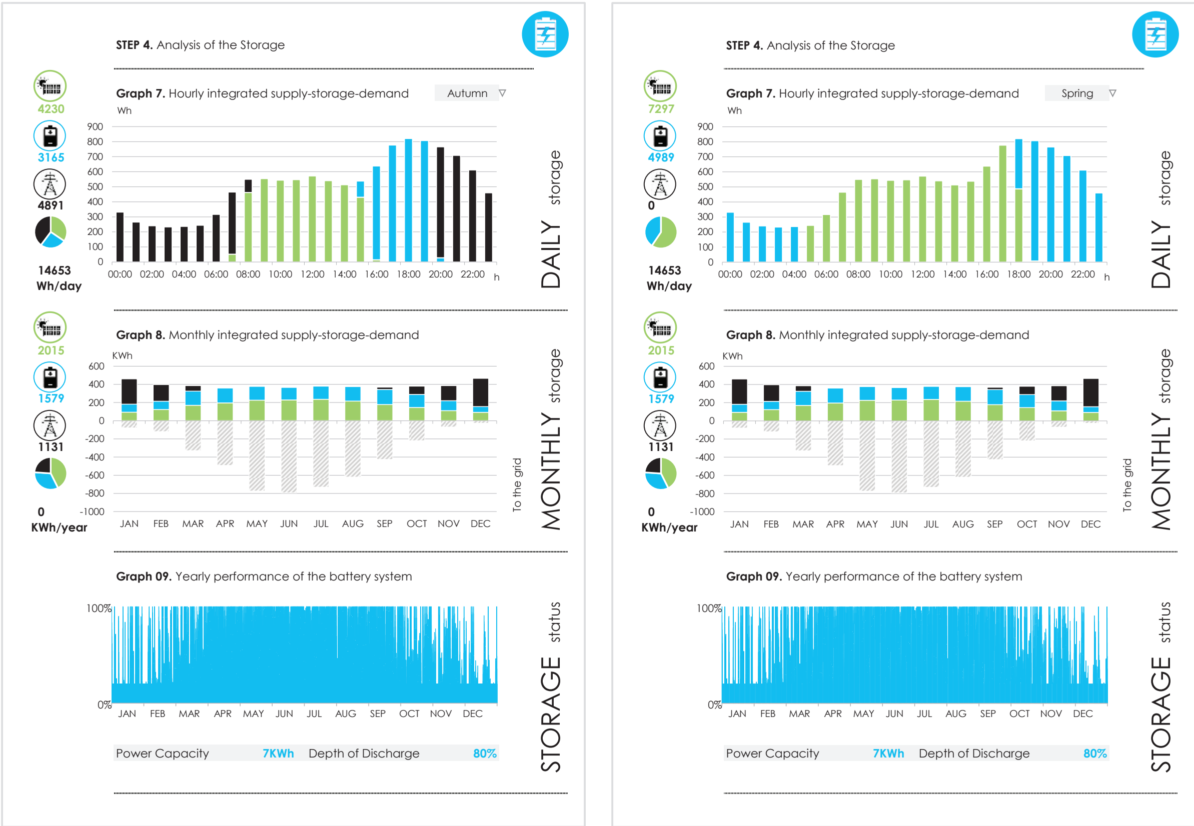

Figure 6. Screenshot of the BAPS Tool – 'Step 4 - Storage'. Left – Storage profiles for SOLCER House case study on a typical day in autumn. Right – The same, but on a typical day in spring.

Graph 7 shows the hourly demand profile and how it is covered with power supplied directly from the renewables generation (green), the battery system (blue) or the grid (black). That is over one typical day in spring, summer, autumn or winter. In graph 8, the bar chart shows the seasonal variations of energy demand, and also how this is covered with energy supplied from renewables, batteries or grid. Also, it shows the monthly feed in of renewable energy to the grid. Finally, graph 9 shows an indicative performance of the battery system across one year by showing battery's hourly operation use as a percentage of its full charge capacity.

3.2. Step 5: Systems' sizing Report.

An optimized sizing process is the final stage of the modelling, to ensure the most efficient and effective balance is achieved between building integrated renewables, battery storage systems and grid based electricity generation. The Step 5, systems' sizing report, is implemented once the assessment tool has completed calculating the energy performance of the whole system and the results have been presented in Steps 2, 3 and 4. The analysis enables the designer to assess the optimum balance between electricity generated at the building, and grid bases supply, taking into consideration the energy demand, the size of the renewable energy system and the energy storage capacity.

The output of this stage is presented in figure 7 for the SOLCER House. Graph 10 shows the building renewables and grid energy supplies for increasing size of solar PV, for the situation without storage. It can be observed that as

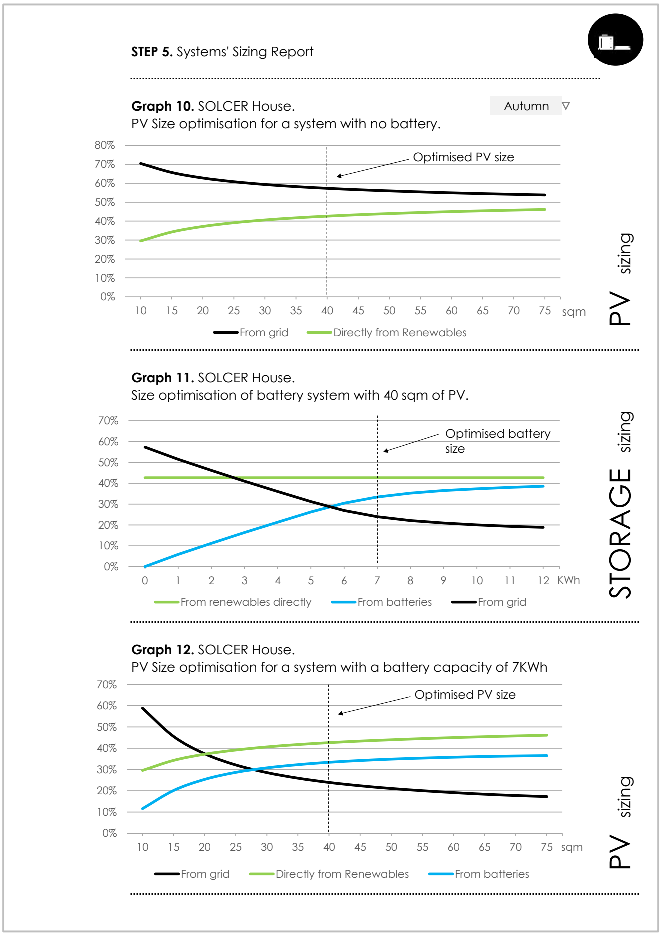

Figure 7. Screenshot of the BAPS Tool – 'Step 5 – Sizing Report'.
Energy profiles for SOLCER House case study.

the area of PV is increased the rate of increase in usable PV energy used in the building falls off indicating an optimum area of PV where the slope decreases (around 25 to 30%). The reason is that because the PV energy generated cannot be stored, its use in the building is reduced. This would then be an argument for exporting to the grid. Graph 11 indicates the mix between the directly used PV energy, the energy used from battery storage, and the grid supply, for increasing battery storage capacity. The area of PV on the SOLCER House is 40m^2, the total area of the south facing roof. The direct PV use is independent of battery size. There is diminishing returns for battery sizes greater than about 7kWh; above this size and a greater area of PV would be needed to significantly improve overall performance. This was therefore the size chosen for the SOLCER House (actually the closest battery size available was 6.9kWh). The final Graph 12indicates the balance for increasing area of PV for the chosen 7kWh battery (although the SOLCER House roof in its current design would not be able to accommodate an increased area of PV). However, it indicates that, for PV areas greater than around 40m^2, the slope of the percentage battery supply falls of, again implying that the system of 40m^2 PV area and a 7kWh battery storage is an optimized solution. There will be iteration between Graphs 11 and 12 in arriving at this optimizes solution.

4. Impact of the proposed research to current literature

The energy system described above can incorporate up to two renewables energy supplies, namely, solar and/or wind, combined with grid supply option, along with an energy storage system; and all within the context of reduced energy demand. The literature suggests that various energy system configurations can be used for power generation, such as PV-wind-hydro systems, biomass-wind-hydrogen cell, PV-wind-diesel systems, etc. [17]. The model presented in this paper, namely, a PV-wind-battery storage system, has been chosen for its capability of being integrated into 'low carbon' building design, which could be applied to new build or retrofit. In the SOLCER House case study only building integrated PV was used, wind being considered too difficult to integrate into the building design. THE BAPS software allows a detailed analysis of options to be carried out during early design stages to optimize the balance across reduced electricity energy demand, renewable supply and energy storage.

Sinha et al [17], in a review of software tools for integrated energy systems identifies and compares 19 different software tools: HOMER, Hybrid2, RETScreen, iHOGA, TRNSYS, iGRHYSO, INSEL, HYBRIDS, RAPSIM, SOMES, HybridDesigner SOLSTOR, ARES, HySim, HybSim, IPSYS, HySys, Dymola/Modelica and SOLSIM. Their limitations, availability and outputs have been compared. Among all these tools, HOMER was considered to be the most widely used tool as it offers more combinations of renewable energy systems and is able to perform optimization and sensitivity analysis. Turcotte et al. [18] classifies these software tools in four categories:

(1) Pre-feasibility tools – mainly used for sizing systems and for producing financial analysis (e.g. RETScreen).
(2) Sizing tools – used for optimizing the size of system's component and for providing detailed data about energy flows among them (e.g. HOMER).
(3) Simulation tools – used for analyzing the behavior of the system, however the user needs to specify the details of each component (e.g. HYBRID2).
(4) Open architecture tools – user can modify the algorithms of the individual components (e.g. TRNSYS).

The BAPS tool offers a combination of these above attributes, in the consideration of different approaches to the energy system design. It is a pre-feasibility tool since the final report 'Step 05' evaluates the cost-effectiveness and the potential of the systems. It is also a sizing tool for both renewable energy integrated systems and electrical energy storage systems. Finally, it is a simulation tool, which analyses the behavior of the whole system by looking at demand, supply and storage profiles. Moreover, BAPS addresses some of the main problems identified from the literature [17], by offering a sensitivity tool with full flexibility, a more user friendly interface, a load demand management, and an economic plan of system cost.

5. Conclusions

The overall aim of this research, combining model development and its actual implementation in the design process, was to develop a 'smart' bottom-up approach to the design of a 'near zero' carbon prototype house. The model as used to determine the optimize balance between building integrated renewable electricity generation and grid based supply, with the focus on achieving a near autonomous solution in electricity use, with the grid used only as a backup when the renewable energy storage system had been depleted. The modelling of the house with the BAPS tool, has indicated that a full energy autonomy solution would be too costly, and inappropriate given the availability of grid energy at the SOLCER House site.

In conclusion, the main aim of the research has been achieved, which was to develop a tool able to assess the potential for the UK's households to become 'Buildings as Power Stations', hence to be active energy generators rather than passive energy consumers, in order to reduce the dependency of UK dwellings on the UK's main power supply grid. However, some improvements on the tool are planned for incorporating other sources for both electrical energy supply and storage, and also, to extend the geographical location beyond the UK climate zones.

The tool has been developed to contribute to further research, including:

- To analyze the impact of the proposed bottom-up approach on the grid,
- To suggest possible reductions of the peaks in the UK power supply grid,
- To identify the relation between the size of renewable systems and the size of storage systems,
- To optimize the combination of renewables such as wind and solar,
- To study the potential to use DC energy in UK households,
- To validate the BAPS tool against measured real data from the SOLCER House case study,
- To compare the cost of converting a standard dwelling into a 'Building as Power Station' producing savings in both CO_2 emissions and energy use.
- To extend the model to combine renewable building integrated heat generation and thermal storage (The SOLCER House also has renewable heat and thermal storage in its design).

A bottom-up approach to the residential sector energy challenge has been presented in this paper, and demonstrated by proposing a building energy systems approach for electrical power. In order to model this type of system, BAPS has been developed as a tool able to include flexibility in the modelling process of energy demand, supply and storage; and to model almost any household in the UK.

Acknowledgements

The SOLCER House project has been funded by the Welsh European Funding Office as part of the Low Carbon Research Institute (LCRI) Convergence Program, led by Cardiff University. The development of the BAPS tool and its application to the SOLCER House design was funded by the UK Engineering and Physical Sciences Research Council (EPSRC) led by SPECIFIC at Swansea University.

References

[1] Business, Enterprise and Regulatory Reform, “CO2 emissions and energy consumption in the UK,” 2008. [Online]. Available: http://www.berr.gov.uk/files/file45404.pdf. [Accessed 9 January 2014].

[2] O. Elma and U. S. Selamogullari, “A comparative sizing analysis of renewable energy supplied stand-alone house considering both demand sied and source side dynamics,” *Applied Energy,* vol. 96, pp. 400-408, 2012.

[3] W. Zhou, C. Lou, Z. Li, L. Lu and H. Yang, “Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems,” *Applied Energy,* vol. 87, pp. 380-389, 2010.

[4] Y. Ru, J. Kleissl and S. Martinez, “Exact sizing of battery capacity for photovoltaic systems,” *European Journal of Control,* vol. 20, pp. 24-37, 2014.

[5] Parliament of the United Kingdom, *Climate Change Act 2008 (C27),* London, 2008.

[6] P. Davies and M. Osmani, “Low carbon housing refurbishment challenges and incentives: Architects perspectives,” *Building and Environment,* vol. 46, pp. 1691-1698, 2011.

[7] X. Shi and W. Yang, “Performance-driven architectural design and optimization technique from a perspective of architects,” *Automation in Construction,* vol. 32, pp. 125-135, 2013.

[8] C. Bleil de Souza, “Studies into the use of building thermal physics to inform design decision making,” *Automation in Construction,* vol. 30, pp. 81-93, 2013.

[9] J. Palmer and I. Cooper, “United Kingdom housing energy fact file,” Department of Energy & Climate Change, London, 2013.

[10] DECC, Energy Saving Trust and DEFRA, “Powering the Nation. Household electricity-using habits revealed,” Energy Saving Trust, London, 2012.

[11] Office for Natinal Statistics, “Population and Household Estimates for the United Kingdom,” Statistical Bulletin, UK, 2011.

[12] Royal Institute of British Architects, “The Case for Space,” RIBA, London, 2011.

[13] Department of Energy & Climate Change (DECC), “Energy Consumption in the UK,” DECC, London, 2013.

[14] Meteotest, *Meteonorm Software, version 6.1,* Bern, Switzerland, 2009.

[15] Welsh School of Architecture, *HTB2 Software, version 2.10,* Cardiff, UK, 2007.

[16] Npower, “Wind Turbine Power Calculations,” The Royal Academy of Engineering, London.

[17] S. Sinha and S. Chandel, “Review of software tools for hybrid renewable energy systems,” *Renewable and Sustainable Energy Reviews,* vol. 32, pp. 192-205, 2014.

[18] D. Turcotte, M. Ross and F. Sheriff, “Photovoltaic hybrid system sizing and simulation tools: status and needs.,” PV Horizon: workshop on photovoltaic hybrid systems, Montreal, September 2001.