A virtual laboratory for the simulation of sustainable energy systems in a low energy building: A case study

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Abstract. The aim of this paper was to develop a virtual laboratory simulation platform of the National Building Retrofit Test-bed at the Cork Institute of Technology, Ireland. The building in question is a low-energy retrofit which is provided with electricity by renewable systems including photovoltaics and wind. It can be thought of as a living laboratory, as a number of internal and external building factors are recorded at regular intervals during human occupation. The analysis carried out in this paper demonstrated that, for the period from April to September 2015, the electricity provided by the renewable systems did not consistently match the building’s electricity requirements due to differing load profiles. It was concluded that the use of load shifting techniques may help to increase the percentage of renewable energy utilisation.

Introduction

The reduction of energy consumption and embodied carbon emissions is a major global challenge. With buildings accounting for a third of global energy consumption [1], upgrading existing buildings and improving building design is crucial in reducing carbon emissions. A holistic approach needs to be taken that considers both supply level and demand level reduction needs in order improve this sector [2]. Reducing electricity demand in buildings can be achieved through the use of energy efficient equipment and lighting, while the reduction of heat loss through a buildings envelope can reduce the amount of thermal energy demand [3–5]. From a supply perspective the use of clean renewable energies such as solar photovoltaics and wind power can reduce the amount of carbon intensive grid supplied electrical energy, leading to reduced carbon emissions. Regarding the investment in and use of these renewable systems; many studies have been carried out to assess financial and environmental implications. Examples of such studies include work carried out in [6–8]. In the European Union, the importance of renewable technologies has increased in recent years as member countries are obliged to meet the goals of the 20-20 by 2020 initiative. The aims of this initiative are to reduce greenhouse gas emissions by 20% when compared with 2005 levels, to increase energy efficiency by 20% and to increase the share of renewable technologies in energy use by 20% by the year 2020 [9]. This paper aims to provide an overview of the National Build Energy Retrofit Test-bed’s virtual laboratory at Cork Institute of Technology, Ireland, while also providing an example of the type of analysis which can be carried out using this platform. This sample simulation was conducted using data from April to September 2015, and analysed electricity use in the building during this period.

Materials and Methods

1.1. Building description
The National Build Energy Retrofit Test-bed (NBERT) [10] (figure 1) is located in the zero2020 building on the main campus of Cork Institute of Technology (CIT). The zero2020 building is an example of a deep building retrofit where part of CIT’s existing main campus building, which was designed in 1974, was upgraded to have a higher level of energy performance [11]. The retrofit project saw both the installation of a variety of sustainable energy systems (figure 2) and upgrades to the existing buildings envelope which led significant energy consumption savings [12]. As an example of a living laboratory the NBERT allows researchers the opportunity to develop and calibrate virtual laboratories to study; microgrid applications, thermal comfort, and demand side management.

Figure 1. Zero2020 building retrofit test-bed

Figure 2. Sustainable energy systems used by the zero2020 building
1.2. Models used for sample analysis

To simulate the output of the 12kWp photovoltaic system on the rooftop of the zero2020 building during a five month period from April 2015 to September 2015, a widely used photovoltaic model [13] was employed. This model consists of a current source with one diode and no series or shunt resistances. It uses the following equations to determine the voltage, current and power of a photovoltaic module at its maximum power point:

\[
V_m = \frac{n N_s k_B T}{q} \ln \left( \frac{n N_s k_B T I_{sc}}{q I_o V_{oc}} \right) \quad (1)
\]

\[
I_m = I_{ph} + I_o - \left( \frac{n N_s k_B T}{q} \frac{I_{sc}}{V_{oc}} \right) \quad (2)
\]

\[
P_m = V_m I_m \quad (3)
\]

Where \( P_m \) = Power at maximum power point (W); \( V_m \) = Voltage at maximum power point (V); \( I_m \) = Current at maximum power point (A); \( n \) = Diode quality coefficient; \( N_s \) = Number of cells in series per module; \( k_B \) = Boltzmann constant (J/K); \( T \) = Cell Temperature (K); \( q \) = Charge on the electron (C); \( I_o \) = Saturation Current (A); \( I_{sc} \) = Short Circuit Current (A); \( V_{oc} \) = Open circuit voltage (V); \( I_{ph} \) = Photocurrent (A).

The inputs to this model included irradiance and ambient temperature data recorded by the for the period specified, as well as specifications of the photovoltaic array. A more detailed description of the materials and methods used, as well as model validation can be found in [14].

To simulate the output of the on-site Proven 2.5 wind turbine (2.5 kWp), a power curve was created by fitting a high order polynomial to data provided by the manufacturer. This curve is shown in Figure 4 and is described by the following equation:

\[
P = au^6 + bu^5 + cu^4 + du^3 + eu^2 + fu + g \quad (4)
\]
Where: \( P = \) Turbine power output (W), \( u = \) Wind speed (m/s), \( a = -0.0025, b = -0.1136, c = 1.717, d = -11.19, e = 55.16, f = -85.2, g = 11.25. \\

The National Build Energy Retrofit Test-bed’s electricity use is logged at hourly intervals and can be divided into three categories; heating, lighting and general services. The electricity consumed by the building during the five month period from April 2015 to September 2015 was used in the sample analysis presented. In order to examine multiple electricity pricing scenarios for the five month period, three electricity tariffs were used. The first tariff used was a flat tariff, which consisted of a constant 24 hour rate of €0.19 per kWh consumed. The second tariff used was a Day/Night (DN) tariff, which consisted of a price of €0.20 from 8:00 to 0:00 and a price of €0.10 from 0:00 to 8:00. The third tariff used was a time of use (TOU) tariff, which consisted of a price of €0.14 from 0:00 to 8:00, and a price of €0.22 from 17:00 to 19:00. To explore the possibility of being paid for exporting electricity, a feed-in tariff (FIT) of €0.10 per kWh was also included in the analysis. As demand side management can yield monetary benefits for varying pricing tariffs [15] two control algorithms were investigated with regard to purchasing and selling electricity; “Grid priority” and “Load priority”. Grid priority implied that all electricity produced by the PV system and/or wind turbine was sold. Load priority implied that only the excess electricity produced by the PV system and/or wind turbine (i.e. remaining electricity after the building load has been met) was sold.

Results and Discussion

**Table 1.** Averaged external conditions for the period monitored

|        | Temperature (°C) | Wind Speed (m/s) | Irradiance (W/m²) |
|--------|------------------|------------------|-------------------|
| April  | 9.3              | 2.7              | 207               |
| May    | 11.1             | 3.0              | 189               |
| June   | 14.1             | 2.5              | 231               |
| July   | 14.6             | 2.8              | 181               |
| August | 14.5             | 2.2              | 161               |
| September | 13.3          | 1.9              | 121               |
Table 2. Building electricity cost (€) over the five month period when using PV, Wind and a combination of both. Negative figures indicate a profit was made (from selling electricity produced by PV/Wind).

| Priority | PV             | Wind            | PV and Wind       |
|----------|----------------|-----------------|-------------------|
|          | Flat DN TOU    | Flat DN TOU     | Flat DN TOU       |
| Grid     | 121.53 9.03 -62.95 | 894.31 781.81 709.83 | 71.54 -40.96 -112.94 |
| Load     | 414.66 302.16 230.18 | 932.76 820.26 748.28 | 403.12 290.62 218.64 |

As can be seen in Table 2, the grid priority algorithm provided substantially lower monetary costs than those incurred using the load priority algorithm. It is interesting to note that the costs incurred when using a wind turbine were similar for both the grid priority and load priority algorithms, whereas the costs incurred when using a PV system varied significantly depending on the algorithm used. The size of the PV system (12kW) compared to that of the wind turbine (2.5kW) was the reason for this difference in cost. In Figure 5, the amount of the building’s electricity demand which was met by the PV system, wind turbine, and a combination of both is shown. In total, 59% of the demand was met by the PV system, 8% by the wind turbine, and 61% by the combination of PV and wind. The building demand over the five month period totalled 4.97 MWh. Interestingly, the PV system produced 8.23 MWh during this period, which would have been more than enough to meet the building’s demand. However, much of this was exported to the grid as excess electricity, due to the power demand of the building not corresponding to the power output from the PV system. The building demand peaked in the morning between 8:00am and 9:00am during the period analysed, as this was the time of maximum occupancy. At this time the PV system was producing little electricity as its peak output occurred during the middle of the day. If load shifting were to be introduced, the PV system output could meet 100% of the building’s demand, while also exporting over 3 MWh of electricity to the grid.

Figure 5: Illustration as to how much of the building’s electricity demand is met by PV, wind and a combination of both during the five month period analysed.
Conclusion

In this study a virtual laboratory for the purpose of simulating renewable energy system in the National Build Energy Retrofit Test-bed at the Cork Institute of Technology was presented. This test-bed was a suitable application due to the amount and variety of data, both internal and external, which is available for analysis. The simulations conducted in the virtual laboratory demonstrated that while the photovoltaic system provided sufficient electricity to meet the building’s demand, it was not possible to do so due to contrasting load profiles. It was deduced that load shifting techniques may allow the building’s electricity requirements to be met, while also providing 3MWh excess for export to the national grid.

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