Quantitative Estimations of the Reduction in Operating Costs and Carbon Emissions of the Cork Community Using the ENTRUST Built Environment Tool

Michael Bennett¹, Mike Oates¹, Giulia Barbano¹
¹IES Ltd, Helix Building, Kelvin Campus, West of Scotland Science Park, Glasgow, G20 0SP

Abstract

Objectives: The aim of this paper is to demonstrate the application of a new prototype simulation tool, ENTRUST Built Environment, to investigate district-level electrical energy generation, consumption and distribution in the Cork community in order to reduce operating energy consumption, cost and carbon emissions. The ENTRUST Built Environment tool is part of a suite of tools designed to address the aims of the ENTRUST project, which are to map Europe’s energy system, develop an in-depth understanding about how human behaviour around energy is shaped by technological systems and drive the adoption of new technologies at a community level.

Methods & Key Outcomes: The ENTRUST Built Environment tool is a high-level design tool that allows users to define simple district models of electricity distribution networks and make quantitative estimations of the impact of various interventions by performing energy simulations. The set of interventions available in the tool includes both building design options and a set of Distributed Energy Resources (DERs), which can represent local or centralised DERs based on their user-specified position in the distribution network. The energy simulations combine calculations of building electricity loads, generation, consumption and/or storage of electricity by DERs and a Virtual Power Plant (VPP) energy aggregation calculation in order to allow simulations of the demand, supply, storage and distribution of electricity throughout the network, including losses, fuel and carbon calculations. Baseline and intervention models are presented for the University College Cork campus, which show that various interventions, such as building retrofit options and the inclusion of renewable DERs, could reduce carbon emissions and operating costs.

Novelty: Simulations of distributed energy systems are nothing new in the literature, but they are often very sophisticated because they need to meet the demands of academic researchers and utilities engineers. Consequently, there is a palpable need for user-friendly, scalable, accurate energy tools that allow urban planners, policy makers, stakeholders and services engineers to make quick and quantitative estimations of the impact of building design options and DERs on urban commodity distribution networks. The ENTRUST Built Environment tool is designed from the ground-up to meet these requirements and provide a tool that integrates building energy loads with district-level aggregation. Consequently, we aim to develop a unique tool that helps to enable the adoption of new technologies by communities, allowing them to make decisions that reduce the operating costs and carbon emissions of DERs and buildings.

Introduction

Urban energy systems

Traditionally, electricity systems have been designed to support economic growth and benefit from developments in generation technology. Typical electricity grids are, therefore, characterised by small numbers of very large generators coupled with a distribution network (e.g. Weedy et al., 2012). However, a number of factors, such as cheaper mass production of smaller energy generators, the climate change challenge and technological advancements in energy generation, transmission and control, are causing urban energy systems to evolve from the traditional, centralised, system to a more decentralised system of generators (e.g. Weedy et al., 2012 or Keirstead et al., 2013). Estimation of the impact of such changes, in advance to their implementation, requires analysis tools. Examples of such tools are MODEST (Henning, 1997), deeco (Bruckner et al. 2003), SynCity (Keirstead, Jennings & Sivakumar, 2012) and EnerGis (Girardin et al., 2010). Recent reviews of the urban energy systems models in the literature conclude that there is a potential to create tools that improve on three main aspects: complexity, data availability and uncertainty in order to provide integrated models that are interpreted in light of the model’s purpose (Keirstead, Jennings & Sivakumar, 2012) and to integrate all aspects of the urban energy planning process into a single tool with a consistent approach (Moghadam, Delmastro & Corgnati, 2017, and references therein). Furthermore, studies of supply and demand of commodities in decentralised systems, specifically, are few with little to no consideration of the energy mix (Hiremath 2005).

The Virtual Power Plant (VPP) concept (Dielmann & van der Velden, 2003) has been proposed as a means to couple decentralized units so they can be effectively managed, by an energy management system, together with centralized ones. The concept was developed further within the context of Optimal Power Flow (OPF) tools as a means to characterise microgrids and/or sets of Distributed Energy Resources (DERs; components of distributed energy...
systems that can provide or manage useful commodities at a district scale, such as PV panels, wind turbines, storage batteries, etc.) as a single, simplified entity (Pujianto, Ramsay & Srbac, 2007; 2008). The aim is to facilitate both the participation of DER owners in the electricity markets and the mitigation of transmission losses and financial penalties due to loss of service. Consequently, VPPs can be further subdivided into Commercial VPPs (CVPPs) or Technical VPPs (TVPPs), with the former primarily concerned with the participation of the VPP in the electricity market to maximise revenue for DER owners and the latter primarily concerned with the minimisation of transmission losses and financial penalties on behalf of the distribution system operator. In this work, we describe the ENTRUST Built Environment tool, inspired by the VPP concept, which aggregates supply and demand. Adopting aggregation as the main calculation methodology allows for very simple and rapid derivations of the total operating characteristics of groups of DERs in meeting the demand set by exogenous loads (cherry-picked from a database of benchmark data) and allows for a quantitative analysis of various interventions without the need for a detailed distributed energy systems model. We also describe some limitations. We then apply the tool to simplified models of the Cork community electricity grid and compare the results with each other to demonstrate the impact of two building-level interventions and one district-level intervention.

The ENTRUST Built Environment tool

The ENTRUST Built Environment tool is a high-level design tool allowing users to perform simple, but rapid, calculations of the energy generation of DERs required to meet an exogenous active power demand and quantitatively assess the impact of a range of possible building or DER interventions. The tool allows users to define buildings as entities and assign parameters to each building that specify the particular equipment present in the building. Each equipment option is graded by its quality and linked to a database of operating power consumption profiles, which is then used as the main input for the tool. Buildings can also be assigned a role in a commodity distribution network; they can have their demand or generation assigned exogenously (via a prosumer unit) or can be assigned a role as a DER, such as a fossil-fuelled power plant, wind turbine or PV array. For example, consider the schematic network shown in Figure 1. In this network, the wind turbine is capable of supplying electricity to node 1, meeting the demand for the attached prosumer unit, and the PV array is capable of supplying electricity to node 2, meeting the demand for the attached prosumer unit. Any residual demand not met at nodes 1 and 2 is passed to node 3. If the role of the building is “prosumer unit”, the building has a demand in the form of benchmark time-series data, which is the result of the collation of meters installed in real buildings (see below for more details). We do not model the building envelope nor its equipment explicitly. If the role of the building is a DER, the supply is allocated in a user-specified order, with the exception of renewable DERs, which always provide the amount generated, even if the amount is a surplus to the total demand. In this paper, we describe a use-case with additional PV panels only, so a supply allocation algorithm is not required. Using aggregation vastly simplifies the problem domain compared to a full distributed energy system model and allows for a straightforward sequential calculation of the aggregated supplies and demands. This allows for simulations of the networks over many scales in feasible time-frames (~seconds on a typical desktop computer for 1000s nodes, generators and prosumers over the temporal domain of 1 year).

However, the main drawback of this aggregation method is the loss of fidelity of the specific energy flows between particular regions and, consequently, the difficulty in specifying network constraints. The importance of network constraints, in particular, was highlighted by Pujianto, Ramsay & Srbac (2007) where the addition of a transmission line constraint with a limit of 10 MW reduced the maximum operating limit of a set of generators from its maximum generation capacity of 40.25 MW to 30.4 MW. In this paper, we therefore stress an important model assumption, which is that the existing transmission infrastructure is capable of allowing the set of generators to generate up to their maximum generation capacity without breaking network constraints.

![Figure 1: Example network schematic, showing the DERs present in a simple network. Prosumer units represent electrical loads and the wind turbine and PV array act as generators.](image)

Models

UCC campus model

Figure 2 shows a schematic map of the University College Cork (UCC) campus, which was the region used for this study. At the campus, 37 buildings were identified for assigning benchmark data, with 10 considered to be “single-family housing” and the remaining 27 considered as “university” buildings.
The Victoria Cross buildings (red circle) and the Castlewhite apartments (blue circle) are assigned the "single-family housing" benchmark data, whereas the remainder of the red highlighted buildings are assigned the "university" benchmark data.

The 10 single-family buildings are located in two clusters, one group of four buildings at Victoria Cross and one group of six buildings, known as Castlewhite apartments (see Figure 2). The building supply was then set-up by considering clusters of buildings located close to each other. This model forms a skeleton by which DERs can be attached. DERs that meet the building loads directly can be attached to nodes close to the clusters of buildings, whereas DERs that can meet demand for additional parts of the campus can be attached to campus-scale nodes. In this study, individual PV panels were attached to all prosumer units so that building loads are met directly by them.

**Scenarios**

Table 1 outlines the set of benchmark data for each scenario modelled and simulated with the ENTRUST Built Environment tool. Scenario 1 can be considered as the baseline/as-is scenario with benchmark data indicative of "poor" building thermal performance and "typical" equipment. For each building type, the list of equipment, with their performance, design option, fuel type, and installation assignment (in this case PV), is specified. For scenarios that include PV panels, a 10kW PV array is added as a DER to each building in the network model.

<table>
<thead>
<tr>
<th>Building type</th>
<th>Performance</th>
<th>Design option</th>
<th>Fuel</th>
<th>10kW PV panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>University</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
<tr>
<td>Single Family terraced</td>
<td>HTG, CLG, HW, PF, IL, SPL, CK, LPL, EL</td>
<td>CLG, LPL, HTG, HW, PF, EL</td>
<td>CLG, PF, IL, SPL, HTG, CK, LPL, EL</td>
<td>-</td>
</tr>
</tbody>
</table>

**Legend**

- Heating (HTG)
- Hot water (HW)
- Internal lighting (IL)
- Cooking (CK)
- External lighting (EL)
- Cooling (CLG)
- Pumps and fans (PF)
- Small plug-loads (SPL)
- Large plug-loads (LPL)
In summary, the five scenarios represent the following cases:
1. As-is building performance, with “typical” design options
2. As-is building performance, with “high efficiency” equipment
3. As-is building performance, with “high efficiency” equipment and PV panels
4. Improved building performance, with “high efficiency” equipment
5. Improved building performance, with “high efficiency” equipment and PV panels

The benchmark data has been collated from numerous sources, including data from over 250,000 buildings in the UK (GOV.UK 2014). This is the dataset used for the ENTRUST project. Time-series data for the “poor” thermal (as-is) building performance is collated from those buildings whose energy consumption (in W/m²) is within the 95% percentile in the dataset, whereas the time-series data for the “excellent” thermal (improved) building performance is collated from those buildings whose energy consumption is within the 5% percentile. “High efficiency” equipment is reduced from the “typical” timeseries values by 14% and 8% for “university” and “single-family housing”.

**PV model**

The PV panels are modelled using the following equations (see, for example, Duffie & Beckman, 2013a). First, the cell temperature, \( T_c \), is calculated using

\[
T_c = T_a + \frac{I_c}{I_{ref}} (T_{nom} - T_{a,ref}),
\]

which is then used to calculate the power, \( P \), using

\[
P = A I_c \eta_c \eta_{nom} \left( 1 - C_F (T_c - T_{c,ref}) \right).
\]

Meanings of the variables are displayed in Table 2 along with choices for the various parameters used. The incident irradiance, \( I_s \), was calculated using the HDKR model (see, for example, Duffie & Beckman, 2013b) for a South-facing, flat-plate collector using historical weather data available for Ireland. Ambient air temperature, \( T_a \), was also taken from the weather data.

**Table 2: List of PV model parameters and variables**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Cell area</td>
<td>92.25</td>
<td>m²</td>
</tr>
<tr>
<td>( C_T )</td>
<td>Temperature coefficient for module efficiency</td>
<td>0.004</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>( \eta_c )</td>
<td>Electrical conversion efficiency</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>( \eta_{nom} )</td>
<td>PV module nominal efficiency</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>( I_s )</td>
<td>Incident irradiance</td>
<td>800</td>
<td>Wm⁻²</td>
</tr>
<tr>
<td>( I_{ref} )</td>
<td>Reference irradiance</td>
<td>800</td>
<td>Wm⁻²</td>
</tr>
<tr>
<td>( T_a )</td>
<td>Ambient air temperature</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>( T_{a,ref} )</td>
<td>Reference ambient air temperature</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>( T_c )</td>
<td>Cell temperature</td>
<td>92</td>
<td>°C</td>
</tr>
<tr>
<td>( T_{c,ref} )</td>
<td>Reference cell temperature</td>
<td>25</td>
<td>°C</td>
</tr>
<tr>
<td>( T_{nom} )</td>
<td>Nominal cell temperature</td>
<td>45</td>
<td>°C</td>
</tr>
</tbody>
</table>

**Costs**

For illustration purposes, we present a crude estimate of the cost of operating UCC campus for a year. The costs are calculated assuming that:

- grid supplied electricity costs a fixed rate of €0.22/kWh;
- the cost of “high efficiency equipment” is €60/m²;
- the cost of upgrading a building envelope to “improved building performance” is €80/m²; and
- a 10kW PV panel costs €5,000 to purchase and install, so the cost for 37 PV panels is €185,000.

The total floor area is 56,547.12 m².

**Results**

Figure 3 shows the grid-supplied electricity for one day (January 1st), out of a 365-day simulation file, for each scenario. The demand is highest at the UCC campus just before and after noon, which is due to the fact that most buildings in the model use the “University” benchmark data. Unsurprisingly, scenario 1 is the worst performing scenario. For this particular day, the incident solar irradiance was very low, so scenarios 2 and 3, which differ only by the inclusion of PV panels, have very similar demands on the grid. The same is true also for scenarios 4 and 5.

The peak electricity demand for this day is 3.1MW for scenario 1 and 0.33MW for scenario 4, demonstrating that the building retrofit options have a considerable impact on mitigating demand.

![Figure 3 – Grid supplied-electrical power for the UCC campus for all 5 scenarios (January 1st). Dashed lines indicate scenarios with PV panels.](image-url)

Figure 4 shows the fraction of total electricity supplied by PV panels for scenarios 3 and 5 for the full year (with the remainder being grid supplied electricity). The 10kW PV panel contribution is much larger for scenario 5 than scenario 3 due to the mitigated demand caused by the retrofit options, which reduces the contribution made by the grid supplied electricity. The total proportion of energy supplied by the PV panels over the full year for scenario 3 is 3.81% and is 24.23% for scenario 5.
These results show that building retrofit options as well as DER options should be considered. We also note that, for scenario 5, there were occasions where the total electricity generated by the PV panels exceeded the total building demand. This allowed a total of 827 kWh of electricity to be exported back to the grid over the course of the year.

Annual summary data for all scenarios is shown in Table 3, including estimates of the total costs, savings and pay-back time for an investment. Since the main reduction in net grid electricity is caused by the improved building envelope, the biggest reduction in pay-back time, costs and CO₂ is caused by this option (compare scenarios 2 and 3 with 4 and 5). However, it is worth noting that the cost of the PV panels relative to the building retrofits is small, providing additional costs savings and CO₂ reduction for a very small change in pay-back time. This is especially the case for scenarios 4 and 5, where the PV panels have a bigger impact on the net grid electricity supplied (25% reduction) and hence the variable costs. The pay-back time is also relatively unaffected by the inclusion of the PV panels.

Table 3: Summary of annual results data for each scenario. The net grid electricity is the difference between the grid supplied energy and the exported energy to the grid. The indirect CO₂ emissions are the CO₂ emissions associated with the grid supplied energy. The fixed cost refers to the renovation cost required to retrofit the existing UCC buildings whereas the variable cost is the cost for the consumption of net grid supplied electricity (with no tariff charge).
References


