Use of Multi-Scale Dynamic Simulation towards the Creation of Positive Energy Blocks

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Abstract

This paper tackles issues related to the development and roll-out of Positive Energy Blocks and Districts (PEBs/PEDs), by using dynamic energy simulation at different scales (building and community) in order to convert existing building groups into PEBs. The research also addresses software developments necessary to enable an integration of dynamic simulation tools into wider decision support platforms that facilitate engagement with various categories of end users, such as local authorities, urban planners, building owners and occupants, as well as citizens.

A historical city centre in Ireland has been taken as a case-study. Both detailed building models and city-wide energy models have been created and simulated with the aim of creating trustful digital twins (Woods, 2019) through which driving the energy transition towards Positive Energy Blocks. Innovative tools have also been used to evaluate the effect that energy interventions and integration of Renewable Energy Systems (RES) would have on the existing electrical grid (Edenhofer, 2011). The use of future weather data has given additional value to the dynamic simulation, enabling climate change to be considered into deployment scenarios projected to the year 2050.

A stepped approach is adopted towards the transition of buildings blocks into PEBs, which outcomes demonstrate that energy efficiency interventions contribute, at least, as much as the integration of RESs. Furthermore, successful roll-out of PEBs entails an active engagement of a wide and diverse range of actors, requiring decision support platforms to be adaptable to each category of end users as well as to different scales of analysis.

Introduction

Specific challenges identified through the Horizon 2020 EU Framework Programme include a Europe-wide deployment of PEBs/PEDs by 2050, considered essential to achieve an energy transition in cities. PEBs/PEDs are most commonly defined as several buildings that achieve a net positive annual energy balance through actively managing their energy consumption and the energy flow between them and the wider energy system (European Commission, 2017).

When a city block is aiming at the objective of reaching the definition of PEB, the local production of energy by itself will hardly be enough to cover the whole energy demand unless the buildings involved benefit from a particularly high energy efficiency. For this reason, it is fundamental to consider the possibility of improving the building envelope and systems prior to consider the local generation of energy. In addition to this, the strength of a so-called PEB also comes from complementary energy consumption profiles among the various buildings, reason for which the premises considered should cover as much as possible different end uses in order to promote a smart and collaborative energy flow.

In this paper, open-source datasets are used as inputs into community-scale dynamic simulation tools in order to estimate the baseline energy consumption of approximately 1000 mixed use buildings, divided into several city blocks. Detailed energy models are also created for 5 buildings located in a single block, and a stepped approach is adopted towards their transition into a PEB, starting from energy efficiency interventions, deployed at building level, followed by the integration of renewable energy systems (RESs) at block scale. The buildings within the block have been chosen in order to constitute enough diversity of end uses to enable the previously-mentioned collaborative energy flow and to analyse how different operational measures could impact different building types. Finally, impacts of such measures on the existing electricity distribution infrastructure are analysed through dynamic virtual network simulation.

Methodology

This section describes the data collection process and the steps for the creation of baseline energy models at both district and block scale, followed by the deployment of energy efficiency interventions and RES integration that have driven the process of moving towards the creation of a PEB. The work is anticipated by an overview of the set of simulation platforms used, as well as the software developments which were identified as necessary in order to enable the whole process of creating Positive Energy Blocks.

Modelling approach overview

The need of finding a unique decision support platform for the various actors, led to the idea of integrating various platforms and software in a unique ecosystem. For the city-scale analyses, the IES Intelligent Community Design (iCD) software has been used to both model and run dynamic energy simulations of the whole district of interest. The IES Virtual Environment (VE) has then been used to create accurate digital twins for only 5 buildings located in the block of interest, for which simulated energy consumption time-series have been linked back to the city-model through the use of the Intelligent Control and Analysis (iSCAN) platform, which also helped during the model validation process. Finally, the city model, together with energy demand time-series for electricity and natural gas, has been exported in the Intelligent Virtual Network (iVN), where the impact of current and future strategies on the existing grid infrastructure could be evaluated, including the addition of new assets such as photovoltaic panels.

Feedback from research consultants, project partners and various stakeholders was collected during the whole process and shared with software developers and product owners. This enabled a smooth and collaborative approach to the development of the various tools which have been shaped to cover and satisfy the needs of a wide range of actors.

Support data

Data identified as relevant to the development of an energy model for the Limerick core city centre, the 'Georgian district', were collected from within a broad and diverse range of sources and formats, and were divided in line with the two different scales of analysis of interest, namely at district scale and at building block level.

At district scale, collection of publicly shareable and non-confidential material from City Council project partner, as well as data extraction from relevant and publicly available national database, such as SEAI (2019a, 2019b), allowed to have strong bases upon which creating the models and/or making reasonable assumptions on missing information. In particular, a Shapefile of the Limerick city centre (Figure 1) has been retrieved from the Limerick City Council, containing building locations, geometries and end uses.

Figure 1: Limerick city centre Shapefile

However, such a Shapefile did not contain any indication on average U-values and construction types for the buildings in the area, thus justifying the use of information from national database to estimate average values of thermal transmittance for the various elements characterizing the envelope of the buildings within the area of interest. In particular, values were filtered considering the Limerick city centre area only, and restricted to buildings with a construction date falling within the Georgian historical period.

The district area of interest includes more than 30 blocks, as illustrated in Figure 1. One of these blocks, which will be referred to as 'Block A' hereafter for consistency purposes, was considered for a more detailed analysis.

For this block, an accurate data collection process took place for five of the buildings within its boundaries. Floor plans and sections have been collected for modelling purposes and a standard data checklist has been developed and completed with details about construction materials, current overall conditions and existing improvements to the building. In addition, the checklist comprehends operational parameters of any HVAC component, as well as typical schedules and occupancy patterns. This preliminary data collection phase was then followed by a site visit by IES consultants to confirm, correct or add value to the collected data. Energy bills have also been collected and used in order to validate the models on a monthly basis.

Finally, information on the electricity distribution network have been provided by the Irish DSO, including the distribution systems and locations of electric substations serving Block A; this played an important role during the grid analysis and the integration of RESs.

Baseline modelling

The Shapefile of the Limerick city centre was cropped to be representative of the Georgian district only, and its relevant information was imported into the iCD software to create the 3D model of this whole area (Figure 2). Constructions, HVAC systems and thermal transmittance values have been assigned to all the buildings populating the model according to the data and assumptions made in the previous section and have been fundamental for the energy simulation.

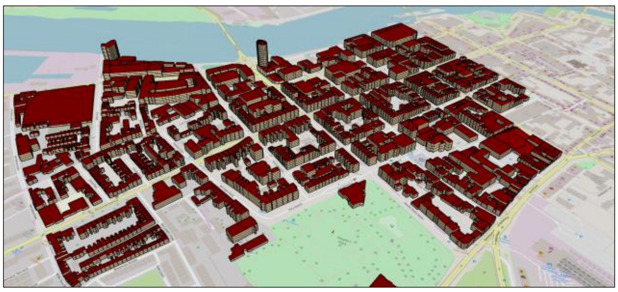

Figure 2: Limerick Georgian district - iCD model.

Building-specific information collected was instead used as a basis to develop, with the use of the VE software, digital twin energy models for 5 buildings located in Block A, as detailed in Table 1. One of the building energy models is also represented in Figure 3.

Table 1: PEB buildings data

Building name	End use	Floor area (m^2)
Building 1	Educational	1,480
Building 2	Commercial	10,234
Building 3	Public Service	787
Building 4	Commercial	766
Building 5	Public Service	449

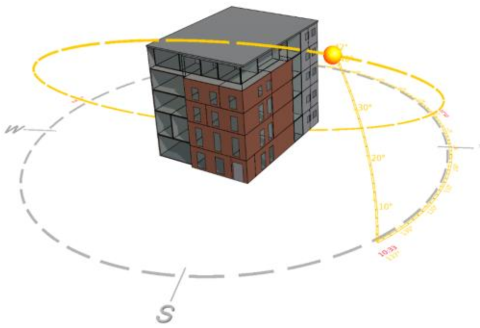

Figure 3: VE energy model of Building 1.

When specific modelling data were missing, model creation relied upon other sources of information (e.g. normative/standard input data), as well as modeller expertise. Reasoned assumptions based on national database were made for some of the inputs of the VE energy models, due to missing support data at individual building level such as, for example, construction materials U-values, HVAC system efficiency and operational parameters, thus potentially lowering the final model accuracy. Other information such as thermal set points, heat gains and ventilation rates, when missing, have been taken from building standards (CIBSE, 2015) and then modified iteratively with the aim of obtaining a digital twin which is as representative as possible of the real building.

The final modelling accuracy has been evaluated using as a target the total energy consumption of each building for a whole year, in order for the model to be comparable to real data collected. However, during the modelling process, electricity and gas consumptions have been monitored and compared separately on a monthly basis, for a more accurate representation of the situation and to have a better understanding of various sources of consumption within each building. Where utility bill data were incomplete, gaps have been filled by performing interpolations according to heating degree days (HDDs) when considering gas consumption for heating purposes, or according to typical appliances usage and schedules when it comes to electricity consumption and base loads. This process helped validating the energy models, i.e. managing to obtain the least possible gap between how the building is performing in real life and its digital twin.

At this stage, the simulated energy consumption profiles (for a whole year, at 60-minutes intervals) for each of the 5 buildings located in Block A have been imported in the iVN tool, which, in addition to the grid information collected, enabled the creation of a virtual network of the whole block (Figure 4).

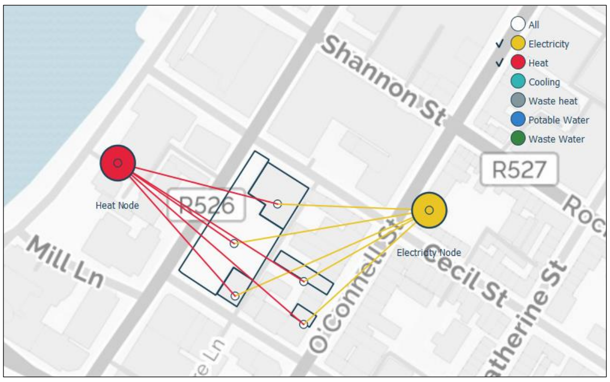

Figure 4: iVN baseline model of Block A.

Building energy efficiency measures

Once accurate baselines of the five buildings located in Block A have been modelled, and the overall energy demand evaluated, focus is moved on bringing the overall consumption towards zero and beyond. This section details the methodology developed and used to pursue the target of net-zero, or positive, energy at a block scale.

First, the poor starting energy performance of most of the buildings under assessment, suggested to apply individual energy efficiency measures (AECOM, 2019) to each of them, in order to start with a significant reduction of the baseline consumption. Careful refurbishment of traditional buildings is, in fact, considered favourable in a climate change mitigation perspective compared to demolishment and rebuild (Duffy, 2019; Berg, 2018).

Both active and passive strategies have been considered, and they have been divided into three main categories according to the intrusion level and assumed upfront cost related to the deployment of each measure – from the lowest level (operational) to medium (shallow retrofit) and up to the highest (deep renovation). This section outlines the general approach and interventions applied. By considering that not all of the five buildings are adequate for the deployment of all of the energy efficiency measures considered, Table 2 illustrates the measures that were applied to each building, while results of reduction in energy demand can be seen in the results section.

Operational (OP) interventions are the least intrusive form of efficiency measures considered. They focus on the intelligent management of those elements such as heating terminals and lighting systems, which can be controlled to avoid unnecessary energy consumption. Below, an explanation of the operational interventions that have been considered:

- **Multi-zoned heating controls (1)**

  Individual room thermostats and heating set points (HSP) replaced the actual uniform temperature distribution within the building. Individual HSP profiles are created for various room types and, if compliant with the heating system available in the building, eventually varying the indoor conditions between a setback temperature (when rooms are unoccupied) and the defined set-point value (when rooms are occupied).

- **DHW heating set-point reduction (2)**

  Review DHW heating set-point, constrained by Legionellae bacteria regulations. Change of hot water supply temperature from 60°C to 45°C

The next step is looking at medium-intrusive measures. Shallow retrofit (SR) interventions do need some manual work to take place, but in a limited manner. They do not require any structural change to the building; their cost and effort level are greater than these required by operational interventions, but they usually guarantee significant energy savings and often improve thermal comfort of building occupants. Below, a detailed list of the shallow retrofit measures that have been considered.

- **Air tightening (3)**

  Reduction of the building air leakage through the application of caulking, sealing, weather-stripping, and use of door sweeps. Minimum air permeability is maintained to ensure adequate air changes as per local codes (DHPLG, 2019).

- **LED lighting system type & dimming (4)**

  Change from existing CFL bulbs to LED lighting technology for all rooms, assuming an illuminance requirement of 500 lux, and light source efficacies of 71.4 lm/W and 95 lm/W for fluorescent and LED lighting systems, respectively. Additionally, implement occupancy-based lighting control and zone daylight dimming for all rooms, including common areas. This was modelled and simulated through the Radiance tool within the VE.

- **Boiler replacement (5)**

  Replacement of the current traditional boiler (sCOP: 0.75) with a condensing boiler with higher seasonal efficiency and adequate size to cover post-interventions loads (sCOP: 0.93)

Finally, deep renovation (DR) works encompass the highest effort level, in terms of costs and time, among all the types of energy efficiency measures. If adequately and carefully evaluated, however, they do lead to the largest energy savings – especially when the starting building condition is particularly poor. Due to the heritage status of many of the buildings in the PEB, and in the whole Georgian District, it was important to evaluate existing restrictions and regulations on the alteration of the building structure and façade, which might be affected by deep renovation measures, as well as possible risks associated with the hygroscopic and thermal behaviour of such buildings (Purcell, 2018). European (European Commission, 2019) as well as national guidelines (CHG, 2011) were considered to take account of this. Below, a list and explanation of the deep renovation measures that have been considered.

- **Roof insulation (6)**

  Addition of an internal insulation layer (thickness: 19,5 mm, conductivity: 0.016 W/(m*K)) to decrease thermal transmittance of the roof; this will also reduce air infiltration rate.

- **Wall insulation (7)**

  Addition of an internal insulation layer (thickness: 19,5 mm, conductivity: 0.016 W/(m*K)) to each exposed wall.

- **Windows retrofit (8)**

  Replacement of the existing single-pane glazing with double glazing mounted on the existing frame, lowering the overall U-value of the whole window system from 3.8 W/(m^2*K) to 0.94 W/(m^2*K).

- **Ground floor insulation (9)**

  Addition of an internal insulation layer (thickness: 39,5 mm, conductivity: 0.016 W/(m*K)) within the ground floor existing construction.

- **Air-to-water HP for space heating (10)**

  Replacement of the existing natural gas boiler with air-source heat pump, with an efficiency of 350% and an overall SCoP of 3.25. If this intervention is considered, intervention 5 (installation of a condensing boiler) will not be deployed.

- **Air-to-water HP for space heating & DHW (11)**

  Replacement of the existing natural gas boiler with air-source heat pump, with an efficiency of 350% and an SCoP of 3.25 kW/kW. Addition of a hot water tank of 200 L with 50 mm factory insulation for hot water storage. If this intervention is considered, intervention 5 & 10 will not be deployed.

- **Demand control ventilation with Heat Recovery (12)**

  Addition of a demand control ventilation with heat recovery to the existing mechanical ventilation system.

Table 2 below summarizes which interventions were applied (y) to each building within the PEB. The reason of excluding particular measures (n) was either due to specific constraints or because the simulation results have shown that the benefit of that measure would not justify its cost.

Table 2: PEB buildings energy measures

Energy measure	B1	B2	B3	B4	B5
OP – 1	y	n	n	y	y
OP – 2	y	y	y	y	y
SR – 3	y	n	y	y	y
SR – 4	y	y	y	y	y
SR – 5	y	n	n	n	n
DR – 6	y	n	y	y	y
DR – 7	y	n	y	y	y
DR – 8	y	n	y	y	y
DR – 9	n	n	y	n	n
DR – 10	y	n	y	y	y
DR – 11	y	n	y	y	y
DR – 12	n	n	y	n	n

RES integration

The next step in the path towards the creation of a PEB is the consideration of renewable energy systems (RESs). Several options were analysed in detail with the help of the intelligent Virtual Network tool, which enabled the dynamic simulation of different strategies and their impact not only in terms of energy production potential but also on the existing electricity infrastructure. The strategy considered in this paper is the installation of photovoltaic panels (PVs) covering an area of two thirds of the available roof space area for all the 5 buildings within the PEB, i.e. 1260 m^2, and sharing the electricity production among the whole block (Figure 5). That particular amount of PVs was chosen as the best compromise between maximizing the available area and avoiding self-shading between subsequent rows of panels. The reason for creating a unique system for the whole block rather than having separate ones for each building, instead, lies behind the concept of PEB itself, which benefits from the sharing of energy among a wider energy system. This means that the electricity generated from PVs installed on a particular rooftop could be used by any of the buildings in the block, avoiding most of the possible waste due to out-of-schedule production (Carli, 2020).

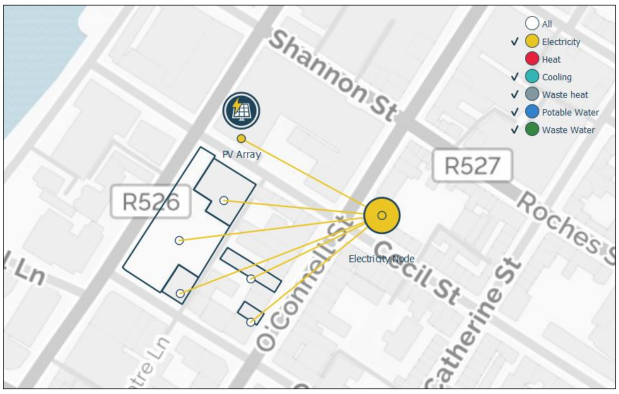

Figure 5: iVN – PV integration in Block A.

While properties of the PVs were collected from manufacturer datasheets of real products (Sunrise Solartech Co., 2020), the orientation and inclination has been chosen to optimize their production, as a result of several trials, which were enabled by dynamic simulation based on solar radiation values from local weather files. A summary of the chosen configuration is shown in Table 3.

Table 3: Photovoltaic Panels characteristics

Total surface area	1,260 m^2
Orientation (from North)	178°
Inclination	32°
Maximum power	250 W
Module efficiency	0.154

Discussion and result analysis

Baseline model

The baseline modelling methodology, as detailed in the previous chapter, allowed to create and simulate the baseline energy behaviour of the whole Georgian district first, and then, with more detail, for the 5 buildings identified in Block A. The results of the dynamic simulation at district scale, performed through the iCD software, are shown in Table 4.

Table 4: Georgian district simulation results

Total Energy Consumption [GWh/year]	Total CO2 emissions [tons/year]
128.8	36,556

While results at district scale could not be verified against real data, a deeper study could be done on results at building scale for the Block A, where, as outlined in the methodology section, results have been validated through comparison against utility bill energy consumption data. During the whole process of model creation and adjustment, gas and electricity consumption figures from the utility bills have been compared on a monthly basis with simulated values from each respective energy model. Figure 4 shows an insight of this process for Building 1, facilitated through the use of the iSCAN platform. For the whole block, a summary of aggregated values of total

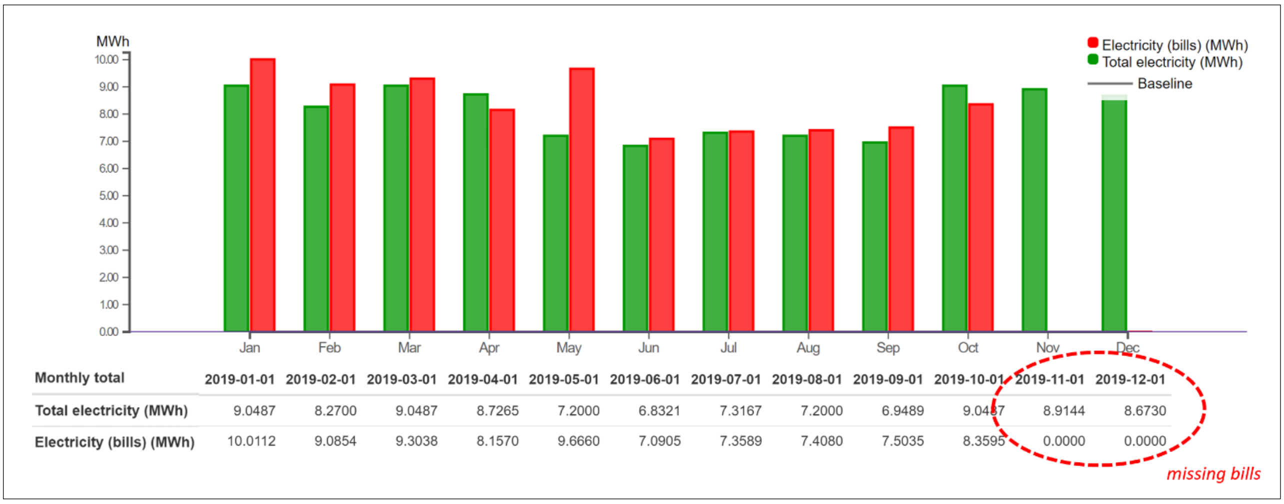

Figure 6: Comparison of real/simulated electricity consumption for Building 1.

energy consumption for the whole block is shown in Table 5. Most of the buildings are within an inaccuracy range of less than 5% difference between real and simulated values at a yearly level, while a quite high discrepancy is found for Building 4 (18%), justifiable by the fact that the energy bills retrieved only covered part of the property, as a whole floor was occupied by external tenants and was thus not possible to verify their energy usage. Building 1, instead, was not part of this comparison as was only recently occupied and thus no energy bills were available yet, but it will be included in future studies. It is interesting to notice that a difference of only 7% has been found between real and simulated data for Block A, as estimated by calculating an average accuracy weighted by each building's total floor area, and excluding Building 2. This result suggests that, when enlarging the simulation scale to multiple buildings, inaccuracies at single building level could be averaged out. This could enable the possibility of using community-scale simulation tools (such as the iCD) for quick assessment of interventions at district/city scale, which validation will be addressed in future studies.

Table 5: PEB buildings simulation accuracy

Building name	Utility Bills [kWh/m^2]	Simulated [kWh/m^2]	Accuracy [%]
Building 1	177.7	174	-2.1%
Building 2	*N/A*	115.1	*N/A*
Building 3	158.9	151.6	-4.6%
Building 4	89.3	105.4	+18%
Building 5	174	115.1	-3.3%
Block A	132.7	123.4	-7%

Building energy efficiency measures

The deployment of energy efficiency measures outlined in the methodology section has been considered following a stepped approach, starting from operational ones and then summing up the savings obtained with the ones from shallow retrofit interventions and, finally, from deep renovation.

By implementing all of the relevant operational measures across the five buildings, as per Table 2, it was determined that a collective saving of 79MWh/year, amounting to a 5% energy saving, could be achieved. However, it should be noted that, notwithstanding Building 2 (which, as a recently refurbished and highly performing building, offered very limited energy saving opportunities) a more substantial energy saving of 13% against the baseline could be seen across the other four buildings combined.

When considered in conjunction with the operational interventions, the shallow retrofit measures brought the combined savings up to 12% (inclusive of Building 2) or 31% (without).

Finally, adding the deep renovation measures to the previous interventions, the total calculated savings amounted to 23% (inclusive of Building 2) or a significant 64% (without). This would improve the efficiency of the block to a high enough level to reduce the local production required to create a positive annual balance as well as ensuring the effectiveness of any installed local production.

RES integration

The integration of Renewable Energy Sources (RESs) was simulated, and in this case it meant the placement of photovoltaic (PV) panels on two thirds (1260m^2) of the collective roof space of all the 5 buildings within the PEB.

After a first high-level analysis of the possible yearly electricity production of PVs, a time-series simulation has been performed within the iVN software in order to have a clearer visualization of electricity demand and generation along the year, thus allowing for an identification of possible over-productions which might lead to electricity being wasted, or else to the necessity of exporting back to the grid. Figure 8, in the next page, illustrates the overproduction of electrical energy from PV panels with respect to the demand on a Saturday afternoon, due to the fact that most of the buildings are closed while PV panels are producing a significant amount of electricity. This surplus of electricity cannot be considered as 'useful production' for Block A, because it is ultimately either wasted or exported back to the grid. The total electricity demand is considered after all of the energy efficiency interventions were applied.

The addition of photovoltaic energy was found to cover 14% of the remaining overall energy demand of the block. Added up to the previous measures, this would mean decreasing the total energy delivered to the block from external, non-renewable sources by 34%. In terms of electricity only, all of the energy efficiency measures combined would reduce the demand for the block to 0.615 GHW/yr. Useful electricity generation from PVs is outlined in Table 6, while an overall summary of energy results from all the analyses performed is shown in Figure 7.

Table 6: PEB electricity demand and generation in [MWh/year]

Electricity demand	Electricity generation	Useful electricity generation	Residual electricity demand
800.0	196.2	175.0	615.0

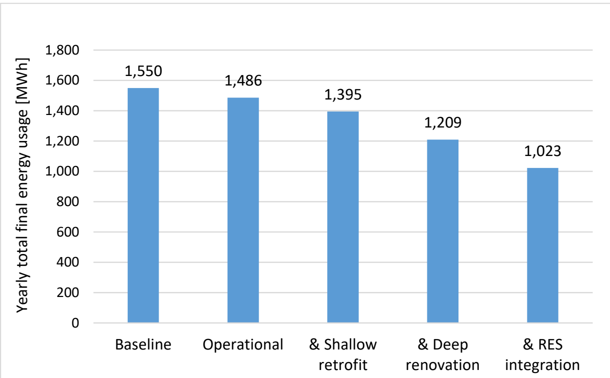

Figure 7: Block A residual energy demand.

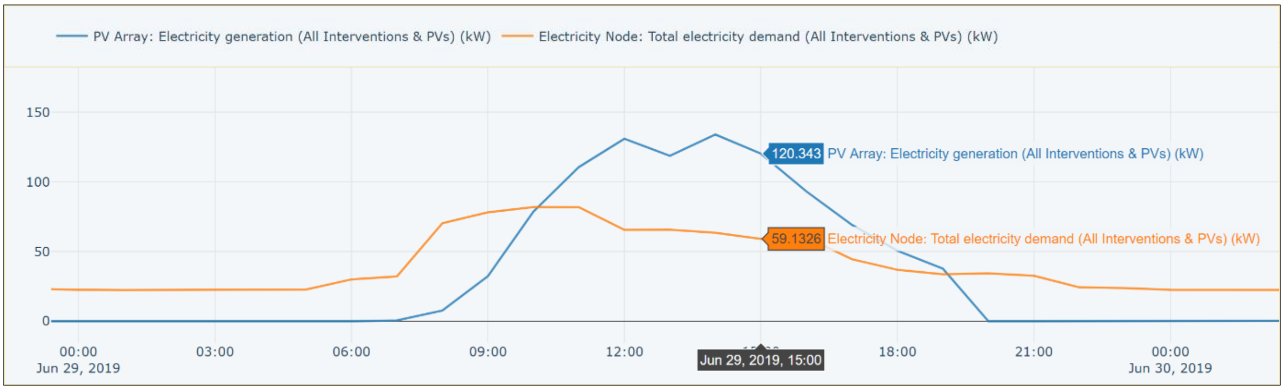

Figure 8: PEB energy demand and generation on a typical non-working day.

Conclusion

The stepped approach adopted towards the transition of building blocks and districts into PEBs/PEDs, demonstrated that the deployment of energy efficiency interventions contributes, at least, as much as the integration of RESs at a block level. Therefore, successful deployment and roll-out of PEBs/PEDs require an active engagement of a wide and diverse range of actors, including local authorities, urban planners, building owners and tenants, citizens.

In order to enable and facilitate this engagement, decision support platforms need to be adapted to each category of end users, thus requiring various simulation scales to be considered, from individual building to blocks, districts and cities.

Further work will include the study of additional RESs to enable the transition of Block A into a Positive Energy Block; also, an accurate modelling of the other PEBs within the Georgian area will be considered, to address the results already obtained by the simulation at district scale, in order to further validate its reliability when it comes to driving decision-making processes. The same process will then be applied to other cities to address its scalability and replicability.

An on-going economical assessment of all the suggested energy interventions and RESs is also being developed, with the idea of including cost-benefit analyses within the broader picture of the decision support platform to facilitate the selection of scenarios to specific categories of end-users.

Finally, an on-going monitoring and verification of the impacts of energy efficiency interventions on the baseline energy consumption will take place in the months / years following their deployment, through the installation of energy meters and sensors whose measured data will be integrated within the iSCAN software and eventually displayed to specific end-users through tailored dashboards.

Nomenclature

PEB	Positive Energy Block
PED	Positive Energy District
EU	European Union
RES	Renewable Energy System
iCD	Intelligent Community Design
iVN	Intelligent Virtual Network
VE	Virtual Environment
iSCAN	Intelligent Analysis and Control
LCCC	Limerick City & County Council
SEAI	Sustainable Energy Authority of Ireland
BER	Building Energy Rating
H2020	Horizon 2020
HVAC	Heating, ventilation, and air conditioning
IES	Integrated Environmental Solutions
DSO	Distribution System Operator
HDD	Heating Degree Day
U-value	Thermal Transmittance
PV	Photovoltaic

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