BUILDING PERFORMANCE SIMULATION OF ADVANCED ENERGY TECHNOLOGIES TO ACHIEVE NET ZERO ENERGY DWELLINGS IN UK

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ABSTRACT

This paper systematically presents the methodology and initial findings from modelling and simulation of advanced energy conservation, generation and management technologies applied to two case study dwellings to achieve a net zero energy (NZE) target. The specific objectives are to meet the Energy Performance in Buildings Directive as follows: reduction of net regulated energy to or below 0 kWh/m^2 per year and generation of at least 50 kWh/m^2 per year, on average, in the NZE settlement. The findings reveal that to meet the specific targets set out for the project aligned with the EU Directive:

- A majority of technological intervention must come from community renewables,
- buildings built to current UK Building Regulations, will need to reduce regulated loads by about half, and
- the NZE targets in particular are not particularly stringent regarding energy efficiency but are highly expectant with regard to renewable energy.

INTRODUCTION

Buildings are central to both UK and EU's energy efficiency policy. Improving the energy performance of UK building stock is crucial, not only to achieve the EU's 2020 targets but also to meet UK"s longer term climate change target of 80% CO2 emission reduction by 2050. The EU 2020 outlines three specific targets to be met by 2020 (relative to 1990 data): reduce greenhouse gas emissions by 20%, increase energy efficiency by 20%, and increase contribution from renewable energy sources equivalent to 20% of final energy consumption (European Commission, 2010).

A key element of the Energy Performance in Buildings Directive (EPBD) recast (Directive 2010/31/EU) is its requirements regarding nearly zero-energy building, which is defined as "a building that has very high energy performance and its nearly zero or very low amount of energy demand is provided by renewable energy systems, which are either on-site or nearby". Directive 2010/31/EU Article 9 requires that member states shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy. The EPBD *nearly zero energy building* definition, as described in Article 2, constitutes a „broad" definition. The Directive lays down the end-results that must be achieved by every Member State. National authorities have to adapt their laws to meet these goals, but are free to decide how to do so (European Concerted Action, 2015; Zero Carbon Hub, n.d.).

This study is part of a major Horizon 2020 research project with case studies in Cyprus, France, Italy and the UK, on design, optimisation, implementation and monitoring of advanced and cost-effective solutions for achieving net zero energy (NZE) and positive energy settlements. This paper focusses on the results of early modelling and simulation of two case study dwellings in the UK. The objectives of this specific study to satisfy the Directive are as follows:

- To achieve a net regulated energy of ≤0 kWh/m^2 per year. The reduced energy consumption will be attained through the application of a number of new technologies.
- In order to achieve the NZE target above, at least 50 kWh/m^2 renewable energy per year must be generated, on average, in the development through either building integrated and/or community renewable systems.

NZE settlements

Another essential feature of the project is to reduce initial investment costs for the case study NZE projects by at least 16% over standard NZE buildings by implementing advanced technological improvement at settlement/ development level. (At this stage in the project, however, costs have not been analysed.)

Until about 15 years ago NZE dwellings were specifically single dwellings built by pioneering developers and architects (Goetzberger et al., 1994; Vale & Vale, 2000) and the NZE drive has largely been focussed on the individual building (Marique & Reiter 2014); however, the settlement scale has advantages in terms of initial investment costs and energy management (Voss, Musall, et al. 2011).

Generally neighbourhoods and communities can support certain technologies for heating, cooling, and electricity generation more cost-effectively through economy of scale. As an example, combined heat and power (CHP) systems are more efficient when larger. Beyond the typical domestic neighbourhood, mixed-use communities benefit from a mix of occupancies and uses, which can support more efficient use of infrastructure, more space for renewable systems, and more efficient use of energy wherein almost 24-hour consumption maximises the use of district heating and power sources (Malin, 2010).

The community level approach can also be helpful in achieving an overall cumulative NZE balance where not all buildings are able to meet the NZE target due to individual limitations (Halasah et al., 2013). The community approach also provides a collective area / shared interest where site-level efficiency measures can be implemented in the common space, e.g. increase pavement reflectivity to impact the local microclimate / reduce the heat island effect.

The case study settlement

The case study dwellings are a part of a new development being built by a housing association in York, England. The community will feature a wide range of different dwelling sizes and forms all served by a gas boiler district heating system. All dwellings have been designed to Level 3 of the Code for Sustainable Homes. The design process reflects a fabric first approach, to ensure that heat loss is kept to a minimum through good thermal insulation, and a good level of air tightness though the scheme has preserved planning permission and only needs to meet 2010 Part L Building Regulations. The case study dwellings will be built in summer-autumn 2016.

Project technologies

In addition to the above energy targets, the project has the goal to apply and test energy efficiency and renewable energy generation technologies that are an advance beyond the state of the art, in order to overcome current shortcomings in new NZE buildings. Particularly in that NZE buildings generally rely on bespoke technologies that are difficult to integrate resulting in complex, inefficient installation and maintenance processes, resulting in high costs (Deng, Wang, and Dai, 2014).

For NZE buildings energy efficiency is essential for success. From an international review, most common among these methods are advanced thermal insulation, advanced solar heat gain design, heat recovery / ventilation, and solar shading (Musall, 2010). Though the dwellings orientation is unable to change as determined by the developer, increased insulation, improved ventilation with heat recovery are methods used to improve the dwellings. In addition to energy efficiency measures, renewable technologies are equally important given the objectives. Table 1 lists the project technologies and their advanced features.

Table 1
Project technologies

NZE technologies	
Adv. Ins. (building level)	Lightweight composite cool thermal insulating extruded polystyrene for high thermal resistance and high solar reflectance
Adv. HVAC (building level)	Solar Desiccant Evaporative Cooling - solar heat and water are used to drive the cooling process
biPV (building/ community level)	Precast, dry-assembled and pre-stressed translucent biPV components made of Dye Sensitized Solar Cells integrated glass blocks - 1 kWp with 8% conversion efficiency requires almost 15-20 m^2
Solar PV and thermal CHP (community level)	Optics technology (lenses or curved mirrors) is used to focus the sun‟s radiation on a small area occupied by one or more high efficiency photovoltaic cells (up to 44% of conversion rate) to generate electricity. Capturing the waste heat increases the overall efficiency of the system and justifies the efforts to develop a CPV/T hybrid technology. (Requires sun-tracking)
WindPV (building/ community level)	Building-based modular wind turbine system that efficiently captures wind energy by exploiting the pressure differences around the building and the solar radiation to generate electricity
Pressurised oil storage (community level)	Thermal storage system used to collect heat from solar fields and transform to cooling by absorption chillers

METHODOLOGY

Using the well-established suite of Integrated Environmental Solution‟s Virtual Environment (IES VE) simulation software and bespoke modelling tools of technology providers, the expected energy performance of the dwellings is simulated and described.

There are three steps to reaching the NZE goal set out in the introduction:

1. Assess and establish the baseline energy performance of the two dwellings,
2. reduce regulated energy consumption to or below 50 kWh/m^2,
3. generate at least 50 kWh/m^2 of electricity from building level and community level renewables.

Because the project deals with an actual development and costs are a real concern, optimisation will be the next step in the project; however, effort has been made to not incur more presumed cost than necessary to meet the targets. However, to further explore reduction, the influence of a building energy management system (BEMS) is simulated to evaluate the potential for further reduction of regulated and un-regulated loads (e.g. lighting).

Definitions

The project targets are only focussed on regulated energy consumption.

- Regulated energy = space heating + cooling + ventilation + domestic hot water (DHW) + fans + pumps
- Renewable energy (RE) = Energy production from building level and community renewables.
- Net regulated energy = (Regulated energy) – (RE)

MODELLING AND SIMULATION

The modelling and simulation process covered five phases:

1. Baseline: the as-designed model,
2. Reference cases: reverse modelling of the baseline to establish reference cases:
    a. Typical reference case, i.e. consumption of typical existing dwelling in England;
    b. UK building regulations reference case: applied building regulations to the model,
3. Baseline+: an improved version of the Baseline model to further reduce consumption though established measures,
4. NZE reduction & generation (NZE_red+gen): a model that combines the technologies to be tested in the project with the Baseline+ model, and
5. NZE_mgmt: a further step to reduce consumption of the composite model with BEMS.

Baseline

The developer for the project selected the baseline dwellings. The dwellings are two-story semi-detached, both with southeast facing entries.

- Dwelling A is a three bed with 110m^2 area on the west side of a semi-detached block and
- Dwelling B is a two bed with 97m^2 area on the east side of a semi-detached block.

Figures 1 and 2 show dwelling A. Dwelling B is almost identical in form and has the same ground floor area.

Fabric U-values, occupancy (three occupants per dwellings), domestic hot water (DHW) consumption, boiler efficiency, and gains were detailed in the Standard Assessment Procedure (SAP) documents provided by the architect.

Operational profiles for occupancy used in the model are those developed by the UK National Calculation Methodology (NCM). The profiles were also used to define DHW, lighting and appliance use.

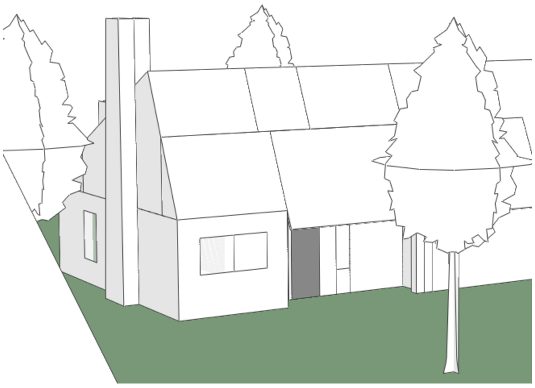

Figure 1 Dwelling A entry

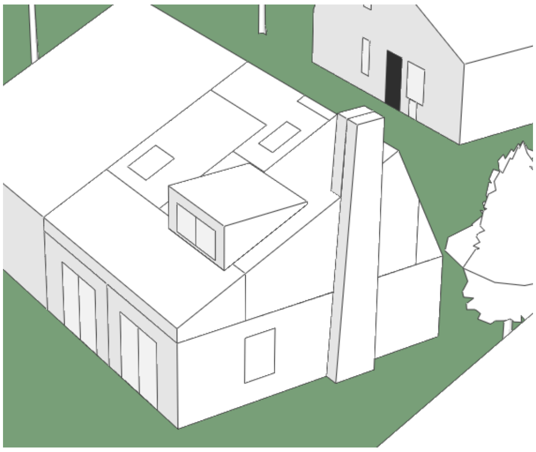

Figure 2 Dwelling A rear and west facing side

Table 2 indicates built details for the baseline dwellings

Table 2
Baseline model characteristics

BUILDING ELEMENT	TYPE	FINAL DESIGN PARAMETER
External wall U-value	Filled cavity wall	0.17 W/(m^2.K)
Roof U-valu	Pitched w/ 185mm insulation	0.15 W/(m^2.K)
Ground floor U-value	Solid	0.15 W/(m^2.K)
Window U-value	Double glazed in uPVC frame	1.3 W/(m^2.K)
Window g-value		0.4
Door U-value	Insulated	1.4 W/(m^2.K)
Design air permeability	6 m^3/(h.m^2)@50pa	
Heating	Gas boiler – district heat (eff. 0.876)	
	Set points: Living: 21^{o}C; all others 18^{o}C	
Mechanical ventilation	**MEV:** Extract only: Kitchen 60 l/s; bathrooms 15 l/s	
DHW	103 L/day	
Heating schedule	Weekday: 07:00 – 9:00 & 16:00 – 23:00 Weekend and holidays: 07:00 – 23:00	

Reference cases

To define the reference building according to typical existing domestic stock in England (Reference Typ.), the most common age group for semi-detached dwellings was selected: 1945-1964 (DCLG, 2015). Typical reference case construction details were obtained from the Tabula & Episcope Building Typology Brochure (2014) but were updated based on the following facts (DCLG, 2015):

- 68% of cavity wall dwellings were estimated to have cavity wall insulation by 2013,
- 80% of all dwellings and 91% of housing association homes were estimated to have more than half of windows double-glazed by 2013,
- 56% of dwellings had 150mm or more of loft insulation by 2013.

For the UK Building Regulation reference case, the current building regulations were used to model thermal design parameters (HM Government, 2013). Table 3 lists the design parameters used where different from the baseline model.

Table 3
Reference cases model design parameters

BUILDING ELEMENT	REFERENCE TYP.	REFERENCE REG.
External wall U-value	0.6 W/(m^2.K)	0.26 W/(m^2.K)
Roof U-value	0.24 W/(m^2.K)	0.20 W/(m^2.K)
Ground floor U-value	0.59 W/(m^2.K)	0.25 W/(m^2.K)
Window U-value	2.2 W/(m^2.K)	1.6 W/(m^2.K)
Window g-value	0.67	0.4
Door U-value	3.0 W/(m^2.K)	1.9 W/(m^2.K)
Design air permeability	15-30 m^3/(h.m^2)@50pa	8 m^3/(h.m^2)@50pa

Baseline+

The Baseline+ version of the models employed an air permeability of 1 m^3/(h.m^2)@50pa; mechanical ventilation with heat recovery; 2 kWp photovoltaic (PV) system; a 4m^2 solar thermal system; and high efficiency lighting and appliances. Aside from air permeability, no fabric changes were made. Figure 3 shows the results for the model for the first three stages.

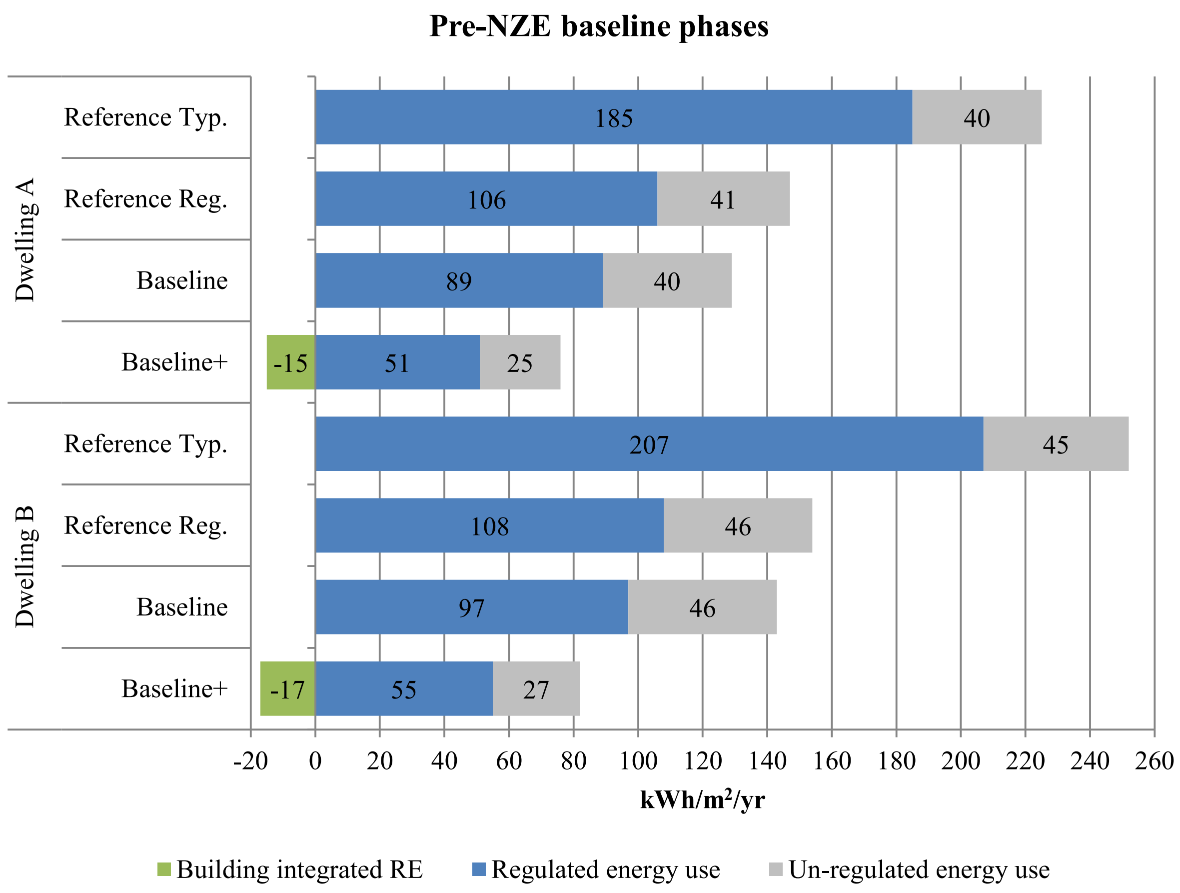

Figure 3 Baseline and reference models results

NZE reduction+generation

Not all technologies introduced for the red+gen stage of the project are relevant to the UK climate. Advanced technologies considered to be relevant and tested include extruded polystyrene insulation with low thermal conductivity (adv. Ins.), building integrated PV (biPV), a solar concentration module which provides thermal and electrical energy (for simplicity named CHP), and a combined solar and wind system (WindPV) (table 4).

Table 4
Modelling details of select technologies

NZE RED+GEN INDIVIDUAL TECHNOLOGIES	
Adv. Ins. (building level)	Modelled in IES VE: additional 100mm of insulation in external walls resulting in 0.11 W/(m^2.K); Additional 110mm of insulation in roof resulting in 0.10 W/(m^2.K)
biPV (building level)	Modelled in IES VE: installed in south roof face; low-e triple glazing with dye-sensitized solar cells integrated
CHP (community level)	Modelled in tech. providers software: solar and thermal power are calculated from solar azimuth, solar elevation (altitude), global radiation, and diffuse radiation
WindPV (community level)	Modelled in tech. providers software: wind and solar power are calculated from wind direction, wind speed, global radiation and solar altitude

NZE management

The energy management model explores automation and the influence of smart user-controls on heating (full control even when not at home) and lighting energy consumption (control and daylighting).

RESULTS & DISCUSSION

The findings from the simulation exercises show that the NZE_red+gen version of the case study dwellings meet the two NZE targets and are actually net plus energy buildings. Table 5 shows the final consumption and generation figures for each modelling phase.

Figure 4 shows the results of each individual technology modelled and simulated / calculated for the NZE red+gen model.

Advanced insulation provides a needed reduction in space heating for the dwellings; however, the insulation material has a slightly higher thermal conductivity than the originally specified insulation in the Baseline model. In the next stage of the project, which involves optimisation and cost evaluation, the two insulation materials will be compared based on their effectiveness and cost, i.e. cost per kWh saved. In addition, one feature that makes the advanced insulation particularly different is that it is coated with a highly reflective surface material. According to the current climate weather year data used for simulation, this is not particularly useful and can be disadvantageous during cold periods but is expected to be useful in the future climate to mitigate overheating risk (Gupta and Gregg, 2012). These different scenarios will be evaluated later in the project.

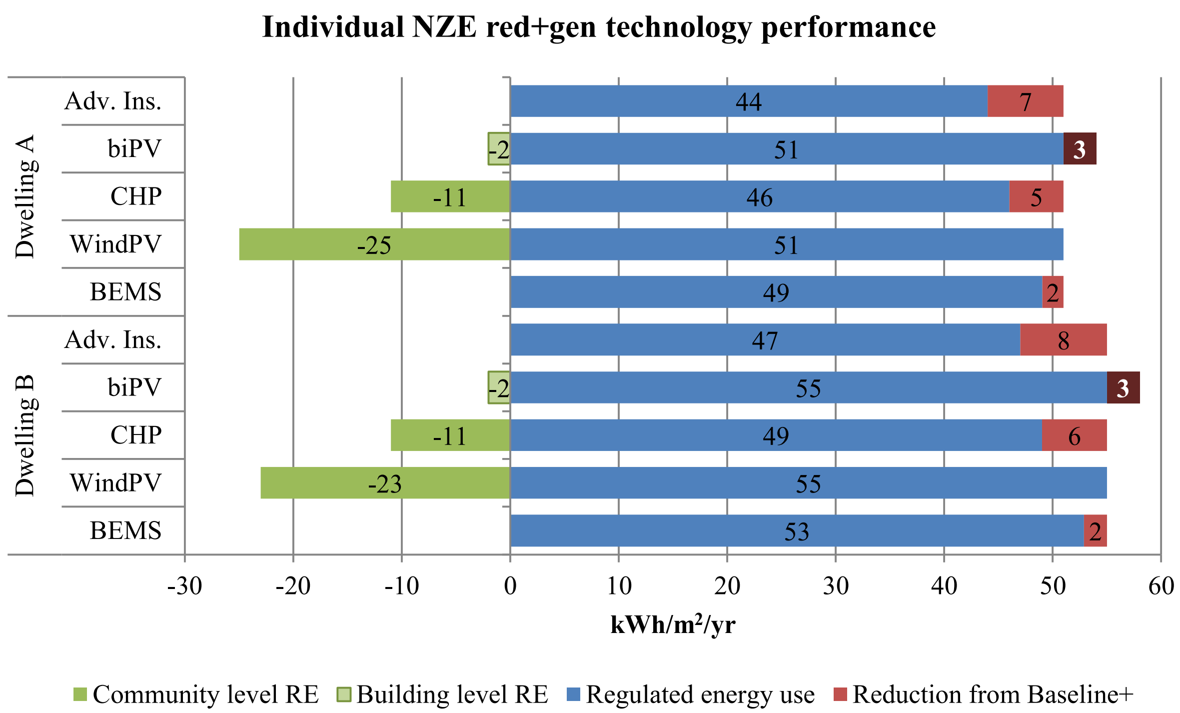

Figure 4 Individual technology performance

Following assessment, BiPV will not be used on the project due to the increase in space heating requirement (dark red block in graph) and small contribution of RE. Based on a preliminary assessment of cost, the biPV is considered inappropriate for the particular case study dwellings even if the fabric of the dwelling were not being compromised by the biPV, that is, if biPV were used on an entry canopy or at community level.

The reduction in regulated energy use by the CHP only considers real time utilisation of the thermal energy by the two case study dwellings based on hourly consumption for each dwelling. The CHP system is however, more effective than it appears because the exported thermal energy not used by the case study dwellings can be utilised by other dwellings in the development, i.e. 100% of thermal and solar generation by the CHP is usable.

BEMS provides a small reduction in space heating from normal contemporary controls, which allow hourly programming, but is more effective with regard to daylight sensing controls (9% reduction in un-regulated energy consumption, not considered for the target).

To improve the models further will require optimisation considering costs, energy reduction and energy generation. As the final models (figure 5) resulted in NZE net regulated figures of -12 and -10 kWh/m^2/yr there is room to reduce energy reduction effectiveness to around zero with the intent to minimise costs whilst meeting the target. As an example, not using the added advanced insulation modelled in step 3 reduces dwelling A‟s NZE net regulated figure to -6. As mentioned above however, the advanced insulation will need to be evaluated against the originally specified insulation. RE generation figures are almost ideal and will likely remain unchanged; however, source and respective costs of RE will be reviewed.

Table 5
Final energy figures baseline and NZE models

DWELLING A (110m^2)				
kWh/m^2/yr	**Baseline**	**Baseline+**	**NZE red+gen**	**NZE mgmt**
Space heating	60	34	25	24
DHW	24	14	12	12
Pumps, fans & ventilation	4	3	3	3
Regulated energy use	89	51	40	39
RE	0	-15	-51	-51
Net regulated energy	89	36	-11	-12
DWELLING B (97m^2)				
kWh/m^2/yr	**Baseline**	**Baseline+**	**NZE red+gen**	**NZE mgmt**
Space heating	65	35	25	24
DHW	27	16	14	14
Pumps, fans & ventilation	5	4	4	4
Regulated energy use	97	55	43	42
RE	0	-17	-51	-51
Net regulated energy	97	38	-9	-10

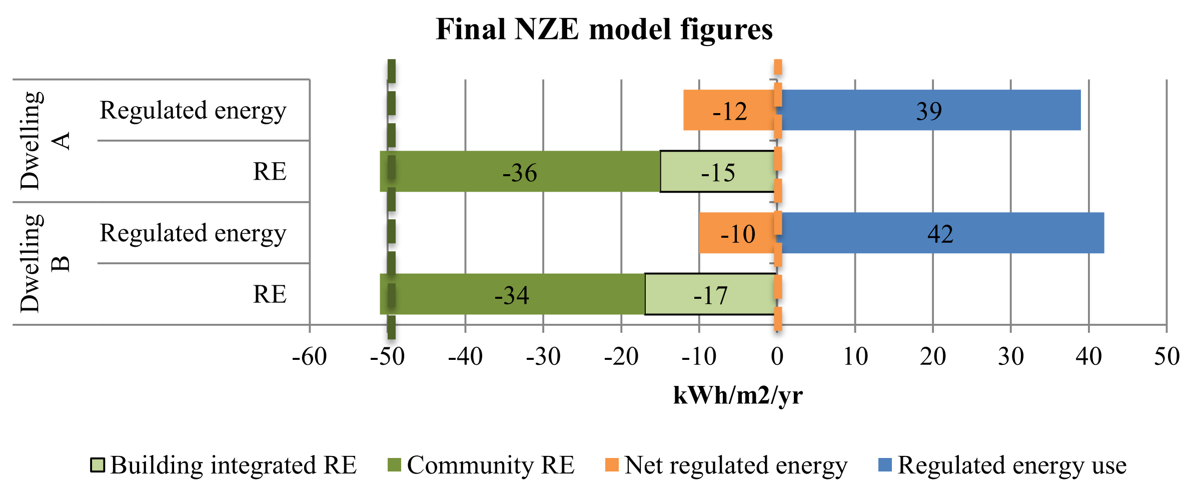

Figure 5 Final NZE model figures

Further work will also include installation and monitoring of effectiveness of technologies. This will be especially interesting for the evaluation of BEMS. With the advancement of BEMS technology there is now integration of more detailed management of energy consumption, e.g. smart phone or other device app control of BEMS and geolocation alerts. Evaluation of the impact of BEMS with these features would require monitoring due to the complex nature of actual use and change in daily patterns.

Finally, the NZE design satisfies the three EU 2020 targets. In detail, this means:

- From the baseline model (more advanced than 1990 levels) the reduction in consumption (not including generation) resulted in a CO_2 emissions reduction of 45% for Dwelling A and 50% for Dwelling B (carbon factors from BRE, 2014). *CO_2 emissions figures are expected to satisfy 'reduce greenhouse gas emissions by 20%,'*
- From the baseline model (more advanced than 1990 levels) the reduction in consumption resulted in an energy efficiency increase of 47% for Dwelling A and 52% for Dwelling B. *Satisfies 'increase energy efficiency by 20%,' and*
- From the baseline model there is an increase in contribution from renewables toward final energy consumption of 70% for Dwelling A and 78% for Dwelling B. *Satisfies 'increase contribution from renewable energy sources equivalent to 20% of final energy consumption.'*

In addition, the dwellings both satisfy long-term UK climate change target of CO_2 emissions reduction by 80%.

CONCLUSION

The paper has demonstrated a valid approach to meeting UK and EU targets outlined in the introduction and discussion. Essentially, not only is it easier to meet these targets, particularly those regarding renewables, by integrating community scale renewables but it is also beneficial to meet targets on a community scale with regard to overall efficiency of implementation, utilisation of renewable energy, and economy of scale.

The findings reveal that to meet the specific targets set out for the project aligned with the EU Directive:

- A majority of technological intervention must come from community renewables,
- buildings built to current UK Building Regulations will need to reduce regulated loads by about half, and
- though the modelled dwellings resulted in greater reductions than necessary, the NZE targets in particular are not as stringent regarding energy efficiency but are highly expectant with regard to renewable energy.

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