

Early-Stage Design Decision-Making for Community Energy Schemes

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Abstract

A model and an assessment framework have been developed to support the transition of residential districts from passive energy consumers to active prosumers linked within Community Energy Systems (CES). Three hypothetic districts form the case studies on which an assumed scenario was applied and examined for the financial, environmental and energy efficiency outcomes it achieves. The case studies consider houses of different types and thermal efficiencies. The results show a promising level of detail, enough to enhance decision-making during the early concept design of projects. The model and assessment framework can evaluate a range of applications including the transformation of old districts into CESs, the expansion of recently built CESs to include adjacent districts with older and usually less efficient dwellings and the designing of CESs for new housing developments.

Introduction

Community Energy Systems (CES) are energy generation, distribution, storage and trading schemes that allow communities to cooperate and efficiently manage their local energy needs through demand-side management and distributed energy resources. Today, they often include integrated new and renewable energy generators. CES can be scaled to meet the needs of all types of communities, rural and urban, from a block of houses in a street all the way up to a whole district (Koirala et al. 2016), (CEM 2009). The complex technical and commercial interactions make the assessment of the business case difficult and impose planning complications. Due to the decentralised nature of CES planning and the wide range of the scopes it may serve, each CES is different and hence each one needs to be studied independently (Acosta et al. 2018).

The advances in information and energy technologies together with the rapid price fall of renewable energy generation have launched an energy transition (Vansintjan 2015). In this new context, communities will have to adopt new roles as they are transformed into active prosumers by producing their own energy within CES (v.d. Schoor & Scholtens 2015). The need for appropriate modelling for the purposes of planning and analysing CESs comes with this rapid energy transition and the new possibilities opening up for the local communities. The modelling of community-level energy

systems calls for detail-based approaches, capable of delivering economic, environmental and, at some level social outputs (Mendes et al. 2011). Due to the many potential benefits of CESs, there is a need for viable tools that account for all the relevant sustainability factors in CES planning and analysis (ibid).

No systematic framework has been developed for techno-economic analysis of distributed multi-energy systems therefore further research is needed on more representative models that capture the operational, economic and environmental value of these systems (Good et al. 2016). The complexity of decisions required at all stages of CES planning, development and implementation is one of the barriers to their implementation (CEM 2009). The decisions are technically complex and few tools exist to support decision making. In addition, there is little awareness among key stakeholders of the potential for CESs to help achieve emissions reduction targets and energy efficiency goals. This is partly because best practices are not well documented, and the benefits are not adequately quantified. Moreover, the tools to identify and analyse opportunities for CESs are not yet available to all the stakeholders (CEM 2009). A systematic and effective tool is needed to facilitate the straightforward analysis of CESs. One that will examine both the demand and the supply side options during the concept development and will assess the viability and the environmental impact of the projects.

This paper presents work towards developing this tool. It introduces and examines the applicability of a model and an assessment framework that have been developed to investigate scenarios for the energy transition of residential districts and to support informed decision-making during the early concept design phase of CES projects. Since typically a CES is formed by a cluster of houses within a distribution transformer (Koirala et al. 2016), the model and assessment framework are initially focused on the modelling of residential areas of such size. The model and assessment framework enable pre-project technical and economic evaluation leaving operational and control optimisation for other, more comprehensive models during the detailed design phase. They are intended for the feasibility study stage of a project where a set of practical and achievable assumptions has to be established in order to carry out the sizing and produce the cost and performance data. Through the assessment of the baseline energy demand

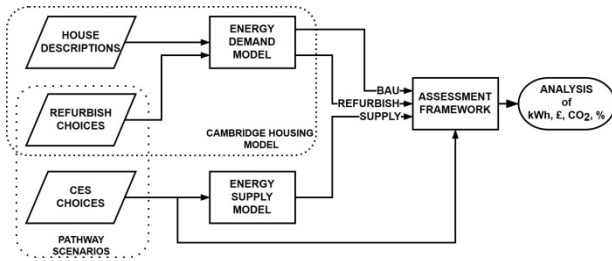


Figure 1: General layout of the model and assessment framework

of districts, the evaluation of the refurbishment potential of the houses and the local energy supply, the model provides the metrics for the integrated assessment framework to measure the benefits of different scenarios for old and new districts. The framework analyses the energy efficiency, the environmental impact and the economic and financial performance of the examined scenarios. The paper explains how the model and assessment framework work and illustrates its application to three hypothetical case study districts loosely based on areas of Nottingham, UK. One of the case studies is the Trent Basin CES (TB 2018), the other is the nearby pre-1900 neighbourhood of Sneinton and the third one is a hypothetical mix of the previous two. Finally, the paper explores the changes in energy demands and costs as the measures of an assumed scenario are applied sequentially and examines whether the assumed scenario maximizes the economic and environmental benefits of community energy implementation for the three case study districts.

Methods

The general layout of the model and assessment framework is presented in Figure 1. It is an expandable, modular, deterministic, mathematical structure comprised of three main sections: Demand Model, Supply Model and Assessment Framework. The models do monthly calculations and the assessment framework evaluates the project for a 25-year period. At first, the energy demand model analyses the demand reduction potential and then the supply model assesses the options for supplying this demand primarily with local energy sources. The energy demand section is based on the Cambridge Housing Model (CHM) (Hughes et al. 2013) to estimate the demand for space heating, Domestic Hot Water (DHW), lighting, electric appliances and cooking and to evaluate the energy savings of the refurbishment options. The model is based on SAP 2009 with adjustments to give more realistic aggregate demand. The energy supply section uses individual sub-models for each technology option to assess the local energy potential, the storage options and the energy flow to and from the community. Finally, the assessment framework analyses the metrics generated from the previous sections to provide insight for informed decision-making. The framework comprises of sub-sections for energy cost analysis, Cost-Benefit Analysis (CBA), financial feasibility assessment and Marginal Abatement

Cost Curves (MACCs). In order to maximise access to the model, it is entirely based on Microsoft Excel.

House descriptions

The principal inputs to the model are the house descriptions which define the location (and therefore the weather), the building envelope, the energy systems and the occupants. The user can select from the CHM's descriptions of 14,951 dwellings drawn from the 2011 English Housing Survey (Hughes et al. 2013). Alternatively, new building descriptions can be entered. Each building has a weighting such that it can be used to represent multiple instances of that type.

Table 1: Description of the housing typologies that were modelled as the communities' dwellings

Typology	Unit	Old End-Terrace	Old Mid-Terrace	New Semi-Detached
Location	-	NTTM ¹	NTTM	NTTM
Total Floor Area	(m ²)	72.2	72.7	110.9
External Wall Area	(m ²)	81.4	55.8	125.2
Window Area	(m ²)	7.2	7.3	21.5
Roof Area	(m ²)	36.1	37.9	50.8
Ground Floor Area	(m ²)	36.1	34.9	41.5
Party Wall Area	(m ²)	42.7	88.4	62.7
Wall U-Value	(W/m ² K)	2.10	2.10	0.13
Window U-Value	(W/m ² K)	4.03	4.03	1.30
Roof U-Value	(W/m ² K)	2.30	2.30	0.13
Airtightness	ach	0.68	0.62	0.84
Heating System	-	Gas	Gas	Gas
HTC ²	(W/K)	377	318	193
Total Energy Demand	(kWh)	23,212	23,080	14,928

¹NTTM – Nottingham

² HTC – Heat transfer coefficient.

Energy demand

The energy demand is estimated by the CHM. Each dwelling is individually assessed firstly for the Business-As-Usual (BAU) scenario, which provides the baseline against which the CES scenarios will be compared. The individual energy demands are aggregated to provide the total for the district. The dwelling typologies that were modelled for the three case studies in this paper are described in Table 1. The refurbishment measures are then applied to all the dwellings. The model considers four refurbishment options: wall insulation, window upgrade, loft insulation and low energy lighting. Table 2 describes the refurbishment options and their effects.

Energy supply

The sizing of the space heating peak demand for each dwelling is calculated as shown by Equation 1, where HTC is the heat transfer coefficient of the dwelling (W/K) and ΔT is the design temperature difference between indoors and outdoors (assumed to be 20°C in these cases).

$$\text{Space Heating Capacity} = HTC \times \Delta T \quad (1)$$

Table 2: Change of dwelling characteristics after upgrade and cost of refurbishment

Demand Side Options	Sol'n	U-Val. (W/m ² K)	Airtightness _s		HTC		Total Energy Demand		Installation cost (£)	Add'l costs (£)	Econ. of Scale (%)	Rebound Effect		Total Cost of Demand Side Options (£)	
			ach		(W/K)		(kWh)					In-Use Factor (%)	Comfort Factor (%)	End-Terrace	Mid-Terrace
			End-Terrace	Mid-Terrace	End-Terrace	Mid-Terrace	End-Terrace	Mid-Terrace							
Wall Insulation	External insul'n (30 mm EPS)	0.60	0.68	0.62	255	235	17,782	19,126	= £57.7 X External Wall Area + £5,330	178	-30% of Total Cost	15%	7,142	6,107	
Window Upgrade	Double Glazing	2.80	0.51	0.47	360	303	22,517	22,439	4,500	28			-	3,170	
Loft Insulation	250mm	0.16	0.68	0.62	300	237	19,777	19,253	300	103			35%	282	
Low Energy Lights	Replace with efficient lighting	-	-	-	-	-	23,100	22,969	100	-			-	70	

The peak DHW demand for all the dwellings is calculated according to the CIBSE CP1 guidelines (CIBSE 2015). The probability of all hot water outlets being in use at any one time is very remote hence the peak DHW demand is subject to a diversity factor according to the Danish Standard DS439 as recommended by CIBSE CP1. The diversity factor for 150 dwellings is given as 0.076. The sum of the aggregated space heating demand and DHW demand of all the dwellings, after the diversity factor has been applied, defines the design capacity of the heating plant for the whole community.

The Solar Hot Water (SHW) calculations are done by CHM's incorporated model which estimates the generation of SHW assuming a solar aperture of 3 m² (Hughes et al. 2013). The Photovoltaics (PV) sub-model is based on BREDEM's technical descriptions and calculations (Henderson & Hart 2013) as shown in Equation 2, where E_{pv} is the PV energy generated (kWh), kW_p is the peak power of the PV (kW), S is the monthly solar radiation (kWh/m²) and Z_{pv} is the overshadowing factor (dimensionless). The monthly solar radiation values come from CHM's climate data for the region of East Midlands and the overshadowing factor was assumed 0.8 for all houses. The model for this paper assumes that half of the dwelling's roof area is available for solar energy systems (PV and SHW), of which SHW is assumed to require 3m², the remainder being PV. This defines the installed capacity of each roof PV system. The size of the PV plant installed in communal area (called hereafter 'communal PV') is calculated according to the land available for the plant, which for this paper was assumed to be equal to the total footprint area of the dwellings.

$$E_{pv} = 0.8 \times kW_p \times S \times Z_{pv} \quad (2)$$

The capacity and the number of the central heat pumps for the district heating network are defined by the space heating and the DHW peak demands. The seasonal CoP of the heat pumps is affected by the source and the output temperatures.

The design of the District Heating Network (DHN) is based on the configuration guidelines for Low-Temperature District Heating by the Danish Energy Agency (Olsen et al. 2014). The flow temperature is 55 °C and the return 25 °C. The DHN sub-section can provide an initial assessment of the pipe size and the network length based on the distribution losses calculations. The losses should be kept below 15% (ibid) and this defines the length and the size of the pipes according to the flow rate as described in Equation 3 and with the use of manufacturer's specifications, where Q_{loss} is the energy losses from the network, c_p is the specific heat capacity of water (kJ/kg°C), \dot{m} is the mass flow rate (kg/s) and dT the difference between inlet and outlet temperatures (°C).

$$Q_{loss} = c_p \times \dot{m} \times dT \quad (3)$$

The introduction of a buffer vessel to the system ensures the reduction of the heating plant capacity and the satisfaction of the peak loads. The capacity required to reheat the buffer is calculated as shown in Equation 4, where P_{buffer} is the power to reheat the buffer (kW), V is the buffer's volume (litres) and dT is the difference between the supply and return temperatures (°C).

$$P_{buffer} = (V \times c_p \times dT)/3600 \quad (4)$$

The buffer vessel can be sized to meet the peak flow rate sustained over a specified duration of time. The total heating plant capacity of the community when a buffer is used is the sum of the capacity required to reheat the

buffer and the capacity for the peak space heating demand (Table 3).

Assessment framework

The assessment framework provides metrics for the evaluation and assessment of the scenario under examination. It comprises economic analysis methods that are well suited for measuring the economic benefits of community energy plans: energy cost analysis, CBA, financial feasibility assessment and MACCs (Cairns 2016).

The energy cost is estimated using UK government's fuel prices projection (DECC 2008). The energy supply equipment costs were sourced from DECC (2009), Dixon (2012), Element Energy (2013) and BEIS (2014). Taxes and standing charges are not considered in the model at this time.

The CBA is used to evaluate the economic and financial performance of the examined scenario. It looks at the initial cost of the investment and the energy cost savings it delivers over time to identify these options that deliver net savings over a period of time (Equation 5).

$$NPV = \frac{Costs - Benefits}{(1 - Discount Rate)^{years}} \quad (5)$$

The financial feasibility examines the simple payback period and the Internal Rate of Return (IRR) of each scenario in order to investigate whether the investment will break even. The simple payback period shows the number of years it would take to recoup the investment. The IRR shows the interest rate at which it will break even and is an indicator of the profitability of an investment. The information from the financial feasibility is used to define cost-effective scenarios that can achieve the community's objectives for decarbonisation and energy efficiency.

The MACCs compare the cost per tonne of CO₂ equivalent (CO_{2e}) reduction for each individual option applied within the scenario. Each box represents a different option. The width of the box represents the emissions reduction potential that the option can deliver compared to BAU over a 25-year period (tCO_{2e}) and the height represents the average net cost of abating one tonne of CO_{2e} through that measure (£/tCO_{2e}).

Table 3: Heating capacity required

Total Required Capacity	Unit	Old	New	Mixed
Space Heating	(kW)	451	611	487
DHW	(kW)	426	426	426
Buffer Vessel	(kW)	279	349	314
Total with Buffer Vessel	(kW)	730	960	801
Total Capacity of GSHPs	(kW)	750	990	825
Total Volume of Buffer Vessels	(litres)	8,000	10,000	9,000

Table 4: Number of dwellings of each type in the three case study districts

Type of Dwelling	Old	New	Mixed
Old End-terrace	30	0	15
Old Mid-terrace	120	0	60
New Semi-detached	0	150	75
Total Modelled Dwellings	150	150	150

The MACCs are ordered left to right from the lowest cost to the highest cost options. Those measures below the X-axis offer the potential for financial savings over 25 years even after the upfront costs have been factored in. Measures that appear above the X-axis are expected to come at a net cost.

Scenarios

Three hypothetical case-study districts were created in order to investigate the applicability of the model and assessment framework. The typology of the dwellings forming the districts was based on dwellings located in Nottingham, UK. The first district was formed by pre-1900 terraced dwellings (hereafter 'Old'), the second by new-built semi-detached dwellings located in the Nottingham Trent Basin development (TB 2018) (hereafter 'New') and the third one was formed by a mix of the old terraced and the new semi-detached dwellings (hereafter 'Mixed') The size of each district totals 150 dwellings (Table 4). The BAU scenario for this paper assumes that all the dwellings are passive energy consumers heated by gas boilers and with no renewable energy generation at all. Each case study district was converted into the same CES. The CES scenario includes both demand-side and supply-side options.

The demand-side options are focused on refurbishment and are therefore only applicable to the old dwellings since they are houses with uninsulated solid brick walls, single glazing and no loft insulation. The new dwellings have insulated cavity walls, triple glazing and 300mm loft insulation. The demand-side options applied to the old houses are external wall insulation (hereafter 'Walls'), double glazing (hereafter 'Windows'), 250mm loft insulation (hereafter 'Loft') and replacing all the existing light bulbs with efficient ones (hereafter 'Lights') (Table 2). The supply-side options include SHW and PV on every roof, a communal PV plant, community battery storage system and district heating network with central ground-source heat pumps and buffer vessels.

For the case studies in this paper, the total rooftop PV capacity for the Old district is 256 kW_p, for the New district 354 kW_p and for the Mixed 305 kW_p. The communal PV for the Old is 288 kW_p for the New is 398 kW_p and for the Mixed is 343 kW_p. Due to the mismatch between the time of PV production and electricity consumption, the PV electricity is assumed to cover only 50% of the demand unless a community battery system (CBS) is installed (FIBP 2013). In this case, all the PV generation, up to the total monthly electricity demand of

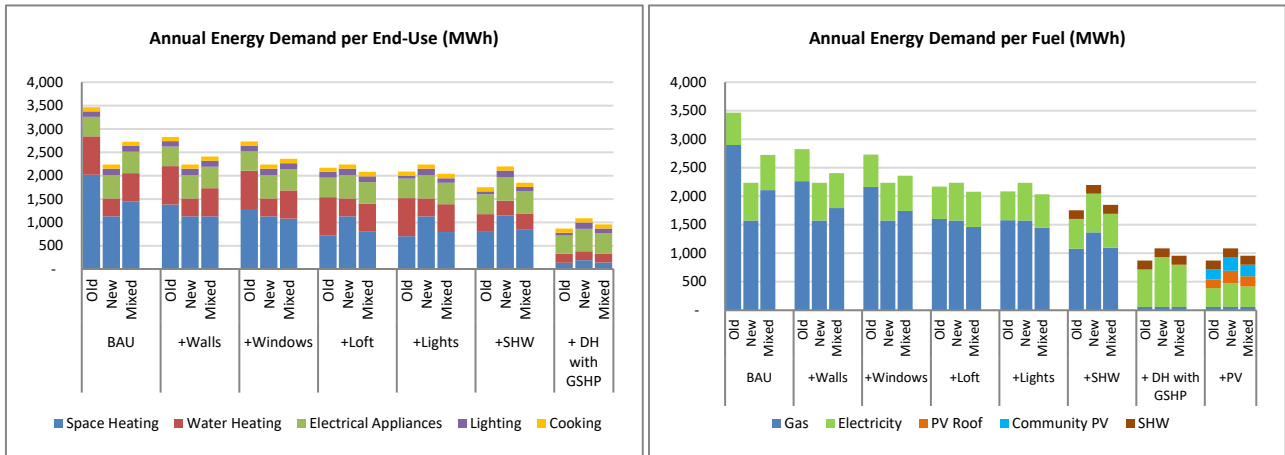


Figure 2: The annual energy demand after applying each refurbishment, energy generation or community energy system option. The graphs show the demand per end-use (Figure 2, left) and per fuel type (Figure 2, right).

the dwellings is consumed within the community and any surplus is exported to the grid. All three case study communities in this paper were assumed to have a CBS.

Ground source heat pumps (GSHP) were modelled for the three case studies. The heat pumps supplying the community heating system were assumed to have a CoP of 3.7 with a lift temperature of 44 °C as calculated by the manufacturer’s data (Dimplex 2013). The selection of the number and size of heat pumps was done according to the equipment sizes available from the manufacturer (ibid).

The three cases are modelled, analysed and compared for the results they deliver.

Results analysis

The cumulative effects of the applied demand-side and supply-side measures on the total energy demand of the districts are shown in Figure 2. Upgrading the building envelope of the Old district’s dwellings has a substantial effect on their space heating demand reducing it from 2016 MWh to 1382 MWh with the installation of external wall insulation then to 1282 MWh with double glazed windows and finally to 723 MWh with the

installation of 250mm loft insulation. The same effect is also noticeable in the Mixed district but to a lesser degree. The installation of solar hot water collectors at the Old dwellings brings down their water heating energy demand from 815 MWh to 365 MWh. The reduction for the New dwellings is from 386 MWh to 316 MWh and for the Mixed dwellings from 600 MWh to 341 MWh. The reduction for the New dwellings is smaller than for the two other cases and this is due to the higher efficiency of their DHW system (89%) compared to the efficiency of the old dwellings’ DHW system (79%).

Gas is replaced by electricity as the main source of primary energy after the installation of the GSHP powered DHN. A small amount of gas is still required though for cooking. The installation of photovoltaics replaces a big portion of the electricity consumed from the grid. Together with solar hot water, they add-up to a renewable ratio of 55% for the Old district, 56% for the New and 57% for the Mixed district.

After all the options have been applied, the total energy demand of the Old dwellings (869 MWh) ends-up being lower than that of the New dwellings (1085 MWh). The

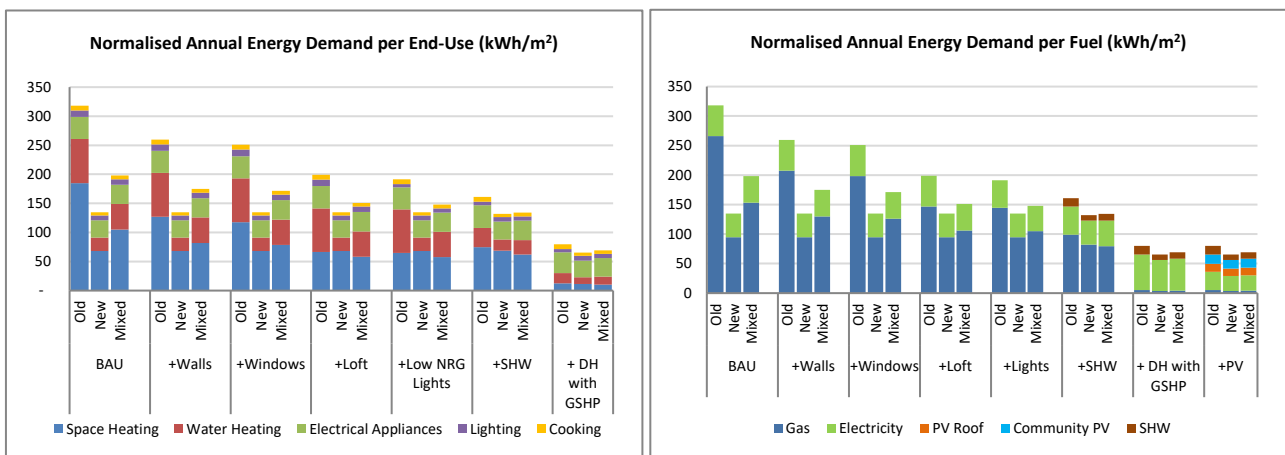


Figure 3: The total energy demand normalised per floor area. The demand is broken-down per end-use (Figure3, left) and per fuel type (Figure 3, right).

Table 5: CBA and financial feasibility assessment data of the case studies

	Unit	Old	New	Mixed
Capital Cost	(thousand £)	4,150	3,144	3,673
	(£/m ²)	381	189	267
Payback	(years)	24	27	26
NPV	(£)	-70,700	-153,300	-122,600
IRR	(%)	-0.9%	-2.8%	-1.9%

Normalised energy demand values though (80 kWh/m² for the Old and 65 kWh/m² for the New) reveal that this happens due to the larger floor area of the New dwellings.

The MACCs of Figure 4 present the cost at which each individual option delivers its carbon reduction potential. The options are ranked in the same order for all three cases, which is: Loft, Lights, Windows, PV, SHW, Walls and DHN with GSHP. There are some variations though to the costs and abatement potentials from case to case. SHW, for example, may be ranked in the same place for all three cases but the marginal costs are different from case to case: 281 £/tCO_{2e} for the Old, 527 £/tCO_{2e} for the New and 201£/tCO_{2e} for the Mixed. The total emission reduction after applying all options to the districts is 79%, 65% and 73% respectively.

The total capital cost of applying all the demand-side and supply-side options of the selected scenario for each district is 381 £/m² for the Old, 189 £/m² for the New and 267 £/m² for the Mixed (Table 5). The higher costs for older dwellings are because of the refurbishment measures needed to upgrade the fabric.

The NPV was calculated at 8% discount rate and is £-70,700 for the Old district, £-153,300 for the New and £-122,600 for the Mixed. The payback period is lowest for the Old district (24 years) which has also the lowest IRR of -0.9% (Table 5). The energy cost shows a

substantial drop in all three cases after all the options have been applied. The cost drops by 76% for the Old district, by 63% for the New and by 71% for the Mixed (Table 6).

Discussion

The analysis of the results and the assessment framework demonstrate that the business case for converting the Old district to a CES is better but is still not profitable using the costs assumed here. The Old district conversion results in higher energy cost saving, better NPV and IRR and the smallest payback period. An interesting outcome of the analysis is that the New district offers a worse business case for the specific CES chosen here. This is because the new dwellings, which are already efficient, leave little room for upgrade and for exploitation of the ‘low hanging fruits’ of refurbishment and hence they are left with only the capital-intensive high-tech solutions of local energy generation. The applied scenario is merely an example scenario for the sake of studying the applicability of the model and assessment framework and by no means represents an ideal or optimised scenario. In this paper, the selected scenario is evaluated for the total aggregated results it delivers. It appears that under the current cost and financial conditions ruling distributed energy generation technologies, there are some options that cannot break even. The scenario achieves remarkable energy demand and CO_{2e} emissions savings, particularly for the case of the Old district, but this does not turn it into an attractive investment unless subsidised somehow. The MACCs can provide an insight on how to re-shape the examined scenario into a better one by removing or replacing one or more options and re-evaluating it.

The work presented in this paper is an initial investigation of the applicability of the model and the assessment framework that have been developed. Future work involves adding wind energy and communal solar hot water modelling modules in order to provide more scenario shaping options with established technological solutions.

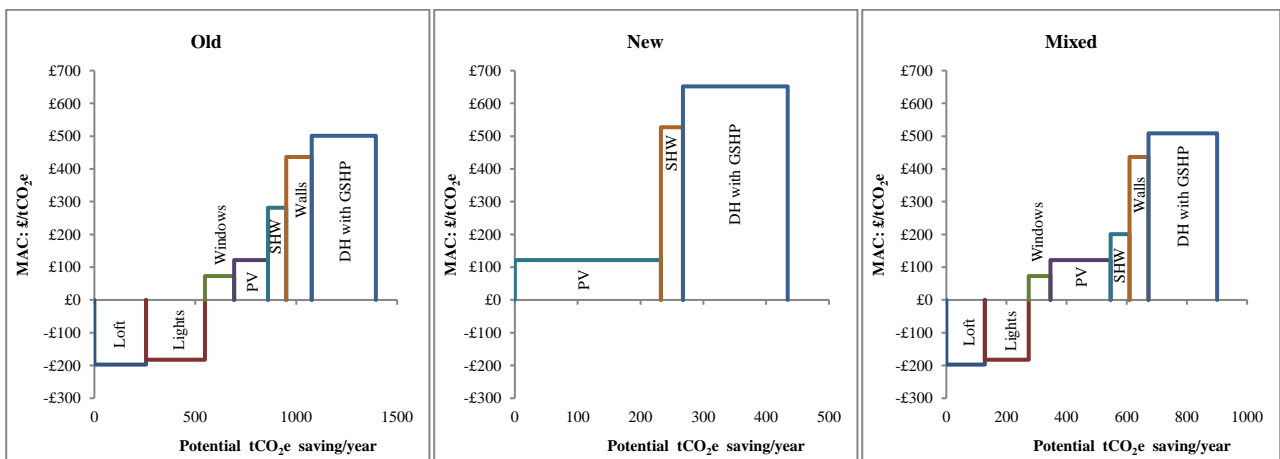


Figure 4: Marginal Abatement Cost Curves for each of the case studies. Each option is evaluated on an individual application basis. The height of the bars represents the abatement cost relative to business as usual and the width represents the abatement potential relative to business as usual.

Table 6: Total Energy, Cost and Emissions of each district.

	Unit	Old			New			Mixed		
		Before	After	Delta	Before	After	Delta	Before	After	Delta
Net Annual Energy Demand	(MWh)	3,466	545	-84%	2,239	636	-72%	2,726	569	-79%
Annual Energy Cost	(£)	225,684	54,230	-76%	185,626	68,378	-63%	200,340	57,966	-71%
Net Annual Emissions	(tCO _{2e})	867	184	-79%	656	231	-65%	737	196	-73%
Renewable Energy Ratio	(%)	55%			56%			57%		

The assessment framework will be accordingly adapted to evaluate the scenarios on a measure-by-measure basis and to assess each option individually. This will provide higher resolution insight on the feasibility and viability of each measure and will help in shaping improved scenarios. The model and assessment framework will be further refined, and the results will be verified. Standing charges and taxes will be added to the energy cost calculations. Furthermore, the inclusion of pricing schemes like the Renewable Heat Incentive and the pricing of ancillary services that can be offered from the CBS to the grid will provide more flexibility to the revenue creation options of the scenarios and will describe the current energy market features in a more representative way.

Conclusion

The paper presents a model and an assessment framework for the investigation and evaluation of alternative refurbishment, renewable energy and community energy schemes. The model and the assessment framework provide a low-cost and undemanding way for modelling and evaluating community energy schemes and their business cases at an early concept design phase in order to assist informed decision-making for an appropriate CES setup that fulfils the goals and objectives of the community.

Analysis is conducted for three theoretical districts of 150 houses located in Nottingham, UK that undergo the same theoretical scenario of transition to active prosumers linked within a CES. The assumed scenario for this paper included, on the demand-side, refurbishing the old houses and, on the supply-side, installing PV with CBS, SHW and DHN with GSHP.

The analysis indicated that the energy and emissions reductions can be substantial, especially for the district with the older dwellings. The chosen scenario provided 55% of the energy from renewable sources, yielded overall energy savings of 84% and a 79% reduction in CO_{2e} emissions. Whilst the energy costs to the households, assuming no change in tariff, was reduced by 76 %, the assessment framework showed that, for these energy costs, there was not a viable business case. Further work will refine and upgrade the financial modelling to assess the tariffs, the cost reductions and the financial regimens that make the business cases viable.

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Nomenclature

BAU = Business As Usual
 CBA = Cost Benefit Analysis
 CBS = Community Battery System
 CES = Community Energy Systems
 CHM = Cambridge Housing Model
 CoP = Coefficient of Performance
 Cp = specific heat capacity of water (kJ/kg°C)
 DHN = District Heating Network
 DHW = Domestic Hot Water
 dT = inlet and outlet temperature difference of DHN (°C)
 E_{pv} = Electricity generated by PV system (kWh)
 GSHP = Ground Source Heat Pump
 HTC = Heat Transfer Coefficient (W/K)
 HTC = Heat Transfer Coefficient (W/m²K)
 kW_p = Peak power of the PV installation (kW)
 LTDH = Low Temperature District Heating
 ṁ = mass flow rate (kg/s)
 MACC = Marginal Abatement Cost Curve
 P_{buffer} = capacity needed to reheat the buffer (kW)
 PV = Photovoltaics
 Q_{loss} = Energy losses from the DHN (kWh)
 S = Annual solar radiation (kWh/m²)
 SAP = Standard Assessment Procedure
 SHW = Solar Hot Water
 V = buffer's volume (litres)
 Z_{pv} = Overshading factor (dimensionless)
 ΔT = indoors and outdoors design temperature difference (°C)

References

- Acosta, C. et al., 2018. Facilitating Energy Transition through Energy Commons: An Application of Socio-Ecological Systems Framework for Integrated Community Energy Systems. *Sustainability*, 10(2), p.366. Available at: <http://www.mdpi.com/2071-1050/10/2/366>.
- BEIS, 2014. Solar PV cost data - GOV.UK. Available at: <https://www.gov.uk/government/statistics/solar->

- pv-cost-data [Accessed March 23, 2018].
- Cairns, S. (SBI/QUEST), 2016. Community Energy Planning Getting to Implementation in Canada. Methods for Measuring the Economics of Community Energy Plans An Introduction for Community Energy Managers. Available at: www.gettingtoimplementation.ca.
- CEM, 2009. *Integrated Community Energy Solutions A Roadmap for Action*, Available at: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oeef/pdf/publications/cem-cme/ices_e.pdf.
- CIBSE, 2015. *Heat Networks: Code of Practice for the UK - Raising Standards for Heat Supply*, Available at: <https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000090MYHAA2>.
- DECC, 2009. The Potential and Costs of District Heating Networks A report to the Department of Energy and Climate Change April 2009. *Energy*, (April).
- DECC, 2008. Updated energy and emissions projections 2013. *The Energy White Paper*, 947(November), pp.1–51. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239937/uep_2013.pdf.
- Dixon, R., 2012. Impact Assessment (IA) Summary : Intervention and Options. , (December), pp.1–24.
- Element Energy, 2013. Review of potential for carbon savings from residential energy efficiency. , (December), pp.1–77. Available at: <https://www.theccc.org.uk/wp-content/uploads/2013/12/Review-of-potential-for-carbon-savings-from-residential-energy-efficiency-Final-report-A-160114.pdf>.
- Good, N. et al., 2016. Techno-economic and business case assessment of low carbon technologies in distributed multi-energy systems. *Applied Energy*, 167, pp.158–172. Available at: <http://dx.doi.org/10.1016/j.apenergy.2015.09.089>.
- Henderson, J. & Hart, J., 2013. BREDEM 2012 – A technical description of the BRE Domestic Energy Model BREDEM 2012. Available at: www.bre.co.uk/5Cn, www.brebookshop.com.
- Hughes, M., Palmer, J. & Pope, P., 2013. A Guide to The Cambridge Housing Model. , (November), p.29. Available at: <https://www.gov.uk/government/statistics/cambridge-housing-model-and-user-guide>.
- Koirala, B.P. et al., 2016. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renewable and Sustainable Energy Reviews*, 56, pp.722–744. Available at: <http://dx.doi.org/10.1016/j.rser.2015.11.080>.
- Mendes, G., Ioakimidis, C. & Ferrão, P., 2011. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. *Renewable and Sustainable Energy Reviews*, 15(9), pp.4836–4854.
- Olsen, P. et al., 2014. Guidelines for Low-Temperature District Heating. *EUDP 2010-II: Full-Scale Demonstration of Low-Temperature District Heating in Existing Buildings*, (April), pp.1–43.
- v.d. Schoor, T. & Scholtens, B., 2015. Power to the people: Local community initiatives and the transition to sustainable energy. *Renewable and Sustainable Energy Reviews*, 43, pp.666–675. Available at: <http://dx.doi.org/10.1016/j.rser.2014.10.089>.
- TB, 2018. Trent Basin - Connecting City Life and Waterside Living. Available at: <https://www.trentbasin.co.uk/> [Accessed March 27, 2018].
- Vansintjan, D., 2015. *The Energy Transition to Energy Democracy: Power to the People*, Available at: https://rescoop.eu/system/files/REScoop_Energy_Transition_to_Energy_Democracy_-_English.pdf.