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Investigating Opportunities for Integration of Existing Distributed Infrastructure to Reduce Carbon Emissions from Domestic Heating

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Abstract: The UK has made some progress towards its carbon emission targets, but in the area of domestic heating less progress has been made. The purpose of this paper is to explore opportunities for achieving reductions in CO_2 emissions by using existing drinking water and wastewater assets as energy storage and recovery mechanisms, coupled with modest local renewable energy generation. This paper explores the sensitivity of the solutions to future projections for domestic heating demands and climate change effects. Simulations optimized the available energy supply, potential for storage, heat recovery and heat demand, to minimize carbon emissions at a scale that could be adopted in most UK towns. It is believed that such an approach may be able to deliver significant carbon emissions reductions with more limited capital investment than more centralized based renewable energy approaches. Results from two UK locations showed that integrated water-energy systems could theoretically reduce CO_2 emissions by about 50%. Furthermore, the system could satisfy demand for about 70% of the time periods over the year. Future scenarios were tested and it was found that the projected annual CO_2 emission reduction, is similar across all scenarios, suggesting that this would be a robust approach.

Keywords: Carbon emissions; water-energy system; renewable energy; residential heat

Introduction

The UK's Climate Change Act was amended in 2019 to target GHG emissions (HMG, 2019). The sixth carbon budget requires a 78% reduction by 2035 compared to 1990 levels. Domestic heat is estimated to account for 15% of the annual UK emissions (BEIS, 2020a). The UK government is currently considering approaches to reduce carbon emissions from domestic heating during the 2020s whilst aiming to reduce reliance on subsidy. A number of technologies are being considered such as heat networks, heat pumps and biogas. However, no consensus exists on what would be the optimum approach. A key challenge for the national decarbonisation of domestic heat is the many small and medium sized towns in the UK, where the bulk of the national population resides. These areas are more challenging than the UK's cities with their higher heat density and associated economies of scale for capital intensive solutions such as district heating schemes. This paper therefore aims to examine potential solutions for such smaller, less dense urban areas and to examine whether the multi-purposing of existing urban infrastructure could provide a technically realistic pathway for small and medium sized towns in the UK and elsewhere to reduce their domestic heating carbon emissions.

Currently in the UK, research has focused on the use of electrical heating, over the longer term the conversion of natural gas heating to utilize hydrogen or in some locations utilizing biogas, and more recently distributed or linked ground/air source heat pumps.

In recent years in Europe, renewable energy sources such as wind and solar have become more exploited (European Union, 2019; Gielen et al., 2019). In several countries heat recovery from water and waste water is being implemented and seen as a promising source of domestic heat energy (Hao et al., 2019, Kretschmer et al., 2016, Heplbasi et al., 2014). A considerable amount of research has focused on heat recovery from Waste Water Treatment Plant (WWTP) (Hao et al., 2019), however with only around 7000 WWTP in the UK, this source is spatially limited. An advantage of heat recovery further upstream in the sewer system is that this is closer to locations of heat demand (Cipolla and Maglionico, 2014). Although less common, there may be potentials in using drinking water systems for heat recovery (De Pasquale et al., 2017; Van der Hoek et al., 2018; Hubeck-Graudal et al., 2020). Hence in some countries the opportunity of utilizing existing water systems for heat recovery and energy storage have started to be explored.

Heat recovered from renewable sources needs to be used close to where is recovered, and be available when required. A key challenge in using renewable energy sources for domestic heating is thus to mitigate both the temporal and spatial imbalance of heat generation and demand (Liu et al., 2020; Spriet and McNabola, 2020; Dagdougui et al., 2012). Dagdougui et al. (2012) proposed the optimal energy flow management within a building characterised by a mix of renewable energy such as wind, solar and biomass to satisfy electricity, heating and water demands. They emphasised the importance of including energy storage systems, as these can halve the daily cost of operating such integrated system. Spriet and McNabola (2020) introduced a novel method that integrates spatial and temporal aspects of effluent heat recovery, and demonstrated the significance of these on the recovered thermal heat.

The aim of this work is to explore the potential of integrated water-energy systems on the UK's carbon reduction target by 2035, to inform investments should be made now to multi-purpose existing water infrastructure and exploit local wind and solar sources. Therefore, the objectives of this paper are to examine: (i) the current performance of an integrated water-energy system, (ii) to explore how the sensitivity of the CO_2 emissions for such a system relate to anticipated scenarios describing potential changes in future heat demand, changes in wind and solar generation due to climate change, reduction in sewage volumes due to future drinking water saving and (iii) to consider the advantages and disadvantages of implementing small-scale community water-energy systems in the drive to significantly reduce emissions from domestic heating

The novelty of the paper is to examine the current performance of an integrated water-energy system, and explore how the sensitivity of the CO_2 emissions for such a system relate to anticipated future scenarios. This paper considers potential changes in future heat demand, changes in wind and solar generation due to climate change, reduction in sewage volumes due to future drinking water saving. The contribution of the paper is that it provides evidence of how linking water and energy systems at a community level could provide carbon emission reductions for domestic heating requirements. It also quantifies the potential heat storage required to ensure that there was no need for an intermittent back up energy source, likely non-renewable. These values could be scaled up from a local community scale to a national scale in terms of implementation.

Material and Methods

Study Area Description

Two different UK case study locations (Gloucestershire and Strathclyde) were selected, to explore regional variations in wind and solar characteristics. Data from 2016-2018 have been used to estimate heat demand that is currently met by non-renewable resources. In this study, a community of 1000 households is considered as the minimum suitable size to represent a local community, such that the variability of heat demand due to variation in individual household demand is small.

Datasets

Hourly domestic gas demand in the UK (UK Data Service, 2007-2010)

The most recent sub-daily measurement of domestic gas demand in the UK is available from a smart meter trial (UK Data Service, 2007-2010), and this dataset was used to estimate heat demand met by non-renewable sources, as it is assumed that most of this gas was used for heating (DECC, 2014).

Hourly wind speed and solar radiation

The simulation is run on hourly intervals, and the optimization aims to find the optimal solar panel area/peak solar power and wind power capacity in Gloucestershire and Strathclyde for 2016, 2017 & 2018. Therefore, hourly wind speed and solar radiation for Strathclyde and Gloucestershire (CEDA, 2016-2018) were used.

Methods of Data Analysis and Evaluation

A random draw of 1000 households' gas demand from the smart-meter trial dataset was done twenty times, which indicated that the variability in gas demand when estimated over a scale of 1000 households is very small ($< 0.21\%$ for the average of the daily mean demands and $<0.43\%$ for the average of the daily mean standard deviation). No local information was associated with this data. Therefore, the average of the twenty datasets was used to produce a representative hourly heat demand profile for a virtual community of 1000 households. UK annual domestic gas consumption has reduced by 11% for 2016, 15% for 2017 and 10% for 2018 compared to 2009 (National Statistics, 2020), hence the 2009 gas demand was rescaled to reflect this. A carbon emission factor of 0.2 $kgCO_2/kWh$ has been used for natural gas (BEIS, 2020b) and 85% of the gas demand currently uses natural gas (CCC, 2018). The carbon emissions of the selected heat demand profile for 1000 households is therefore estimated to be 2262, 2160 and 2288 tCO_2 for years 2016-2018.

Current Environment Scenarios 2016-2018

Liu et al. (2020) developed a model that was used to simulate the integration of five energy sources: wind, solar, potential energy recovery from a drinking water service reservoir, energy from sewer heat recovery and combustion of natural gas (if required). This allows us to examine carbon emission reduction approaches built around small to medium sized towns, which will be needed in the UK if carbon emissions from domestic heating are to be significantly reduced. This model optimises the energy generation capacity for the wind turbine and the area of solar panels, for given amounts of sewer heat recovery and energy storage/recovery in local drinking water service reservoirs, such that the overall system carbon emission is minimized. The model also calculates whether and when a non-renewable back-up system is needed. The model prioritises the sources with the lowest embedded and operational carbon emissions. The carbon emission factor from wind and solar has been assumed to be 0.0107 and 0.0292 kgCO_2/kWh (Bertasiene et al., 2015; Koffi et al., 2017). The model therefore prioritizes heat recovery from existing sewage infrastructure using renewable energy. Energy generated from the wind turbine(s) and solar PV panel(s) is first used to run the sewer heat recovery heat pumps. If not enough recovered sewer heat is available, electricity generated from the wind and water turbine(s) and solar PV panel(s) is used directly to meet the residential heat demand (favouring wind over solar, due to its lower embedded carbon. If there is surplus of wind and solar power after meeting the heat demand, the surplus is used to pump water up to the drinking water service reservoir, which can then be drawn down again when energy is required locally. If there is no wind or solar energy available, water is released from the water service reservoir to generate energy to run the heat pump and/or supply residential demand directly. If there is no energy available from the wind, solar or service reservoir, grid electricity is used to run the heat pump. If all renewable energy fails to meet the demand, a non-renewable source is used as a back-up supply.

The amount of heat recovery from local sewers is based on the assumption that the average water consumption in the UK is 150 litres per day per head (Ainger et al., 1998), and that the wastewater temperature in the vicinity of a heat pump can be lowered by up to 10 ° C with no major impact on the downstream wastewater treatment plant. Kretschmer et al. (2016) demonstrated that the temperature drop at the inlet to the WWTP was a function of the proportion of the overall influent, so a significant temperature reduction may be practically possible as long as the sewer heat recovery location is not close to the WWTP. Abdel-Aal (2018) showed considerable amounts of heat could be taken from a sewer system, with sewage able to recover sufficient heat from the surrounding soil and further downstream wastewater additions, to keep WWTP influent above 10°C. The average daily heat recovery per person from the sewer system is found to be 1.74 kWh (Liu et al., 2020), which is in the mid-range of the values reported from a modelling study applied to a large wastewater collection network (Abdel-Aal et al., 2018). The water service reservoir is assumed to be 1200 m^3, estimated from a daily water consumption including leakage of 250 litres per day per head and the requirement for two-days storage for 1000 households. If 15m head difference, 0.8 pump and 0.6 turbine efficiency turbine is assumed, then such a water service reservoir is able to produce an electricity output of 29 kWh when fully drained.

Future Scenarios up to 2035

The purpose of this section is to assess potential future scenarios up to 2035. A 15-year period was taken as this was thought to be a reasonable working life for the non-renewable energy component (domestic gas boilers) currently used to provide 85% of domestic heating in the UK.

If older housing stock in the UK is gradually replaced with newer, more energy efficient homes, this would be likely to reduce the heat demand in the long-term. The insulation rate has slowed significantly since 2012 (House of Commons, 2019). There has been research to suggest that a reduction of 25% in total energy consumption in residential homes could be achieved by 2035 (Rosenow et al., 2018). However, this could require the rate of domestic insulation to increase by seven times (House of Commons, 2019) and so is considered to be unlikely to occur without drastic central government intervention. Based on maintaining the current rate of domestic insulation, a 3.6% reduction in heat demand was assumed for 2035.

Water consumption is anticipated to reduce, with a value of 115 litres per day per head estimated by 2035 (Artesia, 2018), so also reducing wastewater volumes. Hence for the future scenarios, sewer flows have been reduced in proportion, however, the capacity for the service reservoir has been assumed to remain the same as it has a long design life and would have been built to meet current demand.

The future trend of wind speed and solar irradiance is less well understood, with different studies showing conflicting results. The general consensus indicates a limited change in UK wind speed and solar radiation over the next 50 years (Dawkins, 2019). To investigate potential effects of climate change for 2035, wind speed and solar radiation have therefore been changed by a modest +/-5%.

Results and Discussions

Current Environment Scenarios 2016- 2018

Table 1 shows the potential reduction in carbon emissions of an optimized integrated water and energy system, resulting from the simulation model of Liu et al. (2020). Table 2 shows the optimum wind turbine size and solar panel area. Strathclyde has fewer solar hours and lower levels of irradiance in general, but a higher average wind speed, from the obtained data from Met Office (CEDA, 2016-2018). Wind turbines with higher cut-in, cut-out and rated wind speed are applied in Strathclyde. There are weather variations between the three different years, and the simulations have shown that they can have a significant effect on estimating the optimized solar panel area and wind capacity. Carbon emissions levels are relatively stable at both locations and there is small, but systematic variation between locations. There is a similar pattern for carbon emissions free hours per year (Table 3), relatively stable but systematic variation between locations.

Table 1: Total carbon emission and percentage reduction for 1000 households in the two UK locations, for optimized wind turbine and solar panel area, compared to heat demand met by natural gas.

Year	2016		2017		2018	
	tCO_2	reduction	tCO_2	reductio n	tCO_2	reduction
Gloucestershire	1091	52%	1045	52%	1000	56%
Strathclyde	1091	52%	1071	50%	1206	47%

Table 2: Optimal solar panel area/peak solar power and wind power capacity in Gloucestershire (G) and Strathclyde (S) that minimizes CO_2 emissions

Year	2016	2017	2018
Solar (m^2)	G: 4155	G: 6193	G:4717
	S: 13483	S: 8868	S: 11106

Solar power (kW)	G: 516	G: 786	G: 602
	S: 1693	S: 1124	S: 1411
Wind (kW)	G: 8014	G: 7927	G:7489
	S: 9498	S: 9097	S: 11861

Table 3: The percentage of hours that the integrated system totally satisfies heat demand with no CO_2 emissions within the simulated period.

Year	2016	2017	2018
Gloucestershire	71%	72 %	73%
Strathclyde	67%	70%	63%

To illustrate the daily variation and mis-match in heat demand, and supply from the different renewable sources, hourly supply proportion and surplus from the different sources from two randomly selected winter and summer days are shown in Figures 1-4. In winter, heat demand is large and the renewable sources are not able to satisfy the demand for many hours. Heat recovery from sewers and solar generation is less than 10% compared to the output from wind. During the winter day, there is no sewer heat surplus, wind has surplus production during some periods, however, solar has only very limited surplus for both locations. A non-renewable energy source is often needed. The peak value of the non-renewable supply is 7311 kWh in Strathclyde and 8037 kWh in Gloucestershire over the year. The reservoir is drawn down at hour 23 in Gloucestershire and hours 1, 4, 16 and 25 in Strathclyde, although with a maximum electricity output of 29 kWh, this is difficult to visualise on the graph.

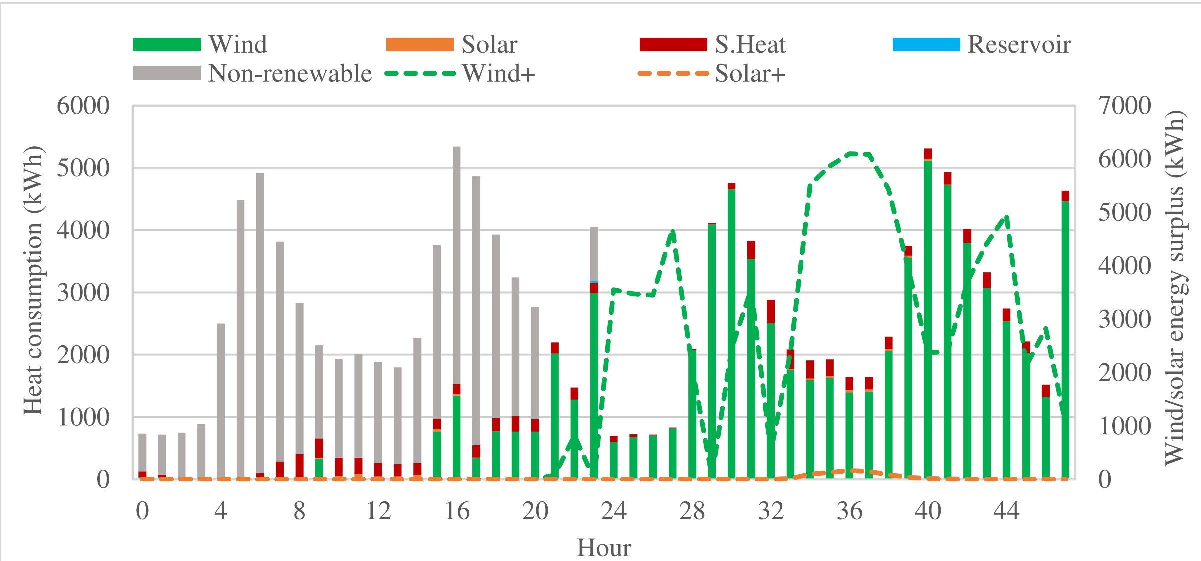

Figure 1: The supply proportion and surplus from wind/solar on two randomly selected winter days (3-4 Feb, 2018) in Gloucestershire. The secondary vertical axis displays the surplus from wind (denoted by Wind$^+$) and solar (denoted by Solar$^+$).

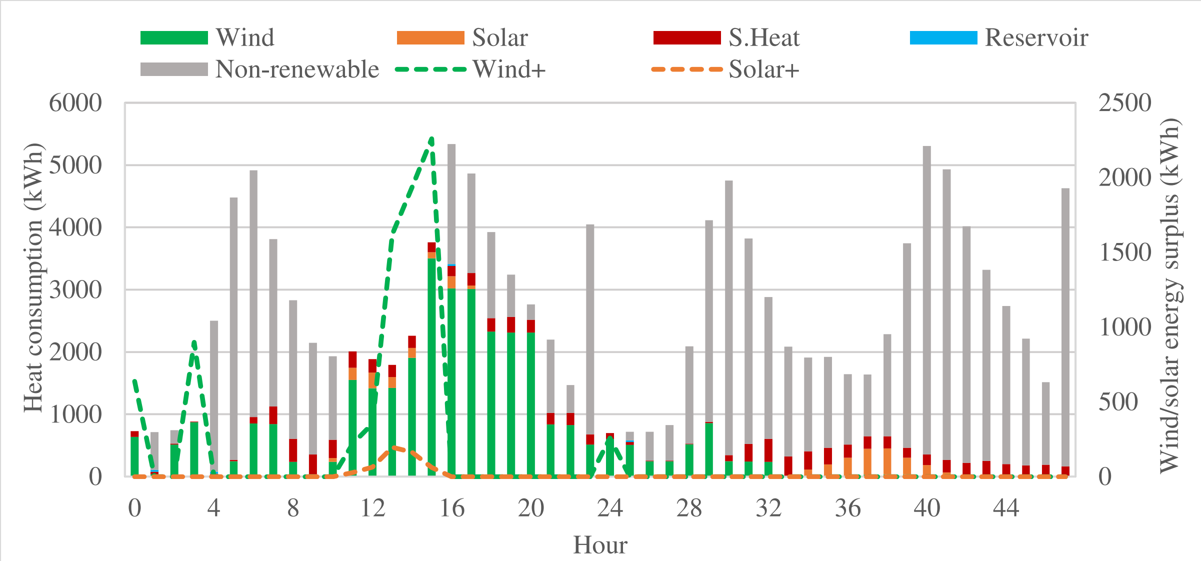

Figure 2: The supply proportion and surplus from wind/solar on two randomly selected winter days (3-4 Feb, 2018) in Strathclyde. The secondary vertical axis displays the surplus from wind (denoted by Wind^{+}) and solar (denoted by Solar^{+}).

In summer, overall demand is about seven times less than in the winter. The heat recovery from sewers alone is able to meet the heat demand for many hours and still has surplus for a few periods. Including wind, solar and the amount of energy stored in the service reservoir, the integrated system could cover the demand for many of the periods in both locations, but in both locations a non-renewable source is still needed for some small periods to ensure continuity of supply (Figures 3&4).

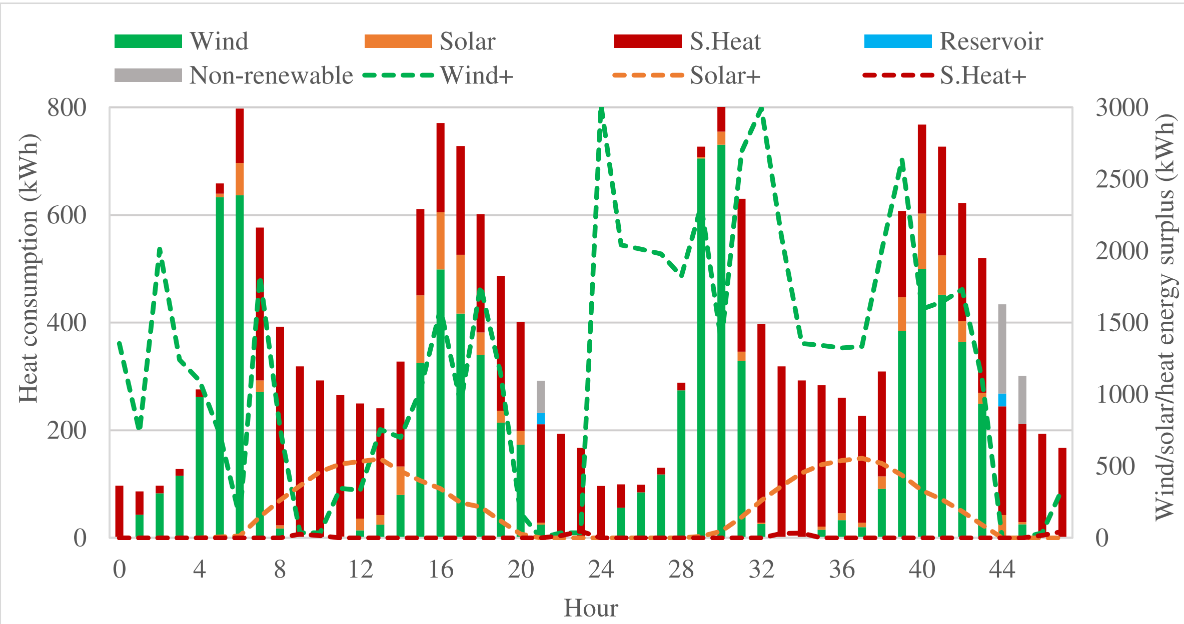

Figure 3: The supply proportion and surplus from wind/solar/heat on two randomly selected summer days (7-8 Jul, 2018) in Gloucestershire. The secondary vertical axis displays the surplus from wind (denoted by Wind^{+}), solar (denoted by Solar^{+}) and sewer heat (denoted by S.Heat^{+}).

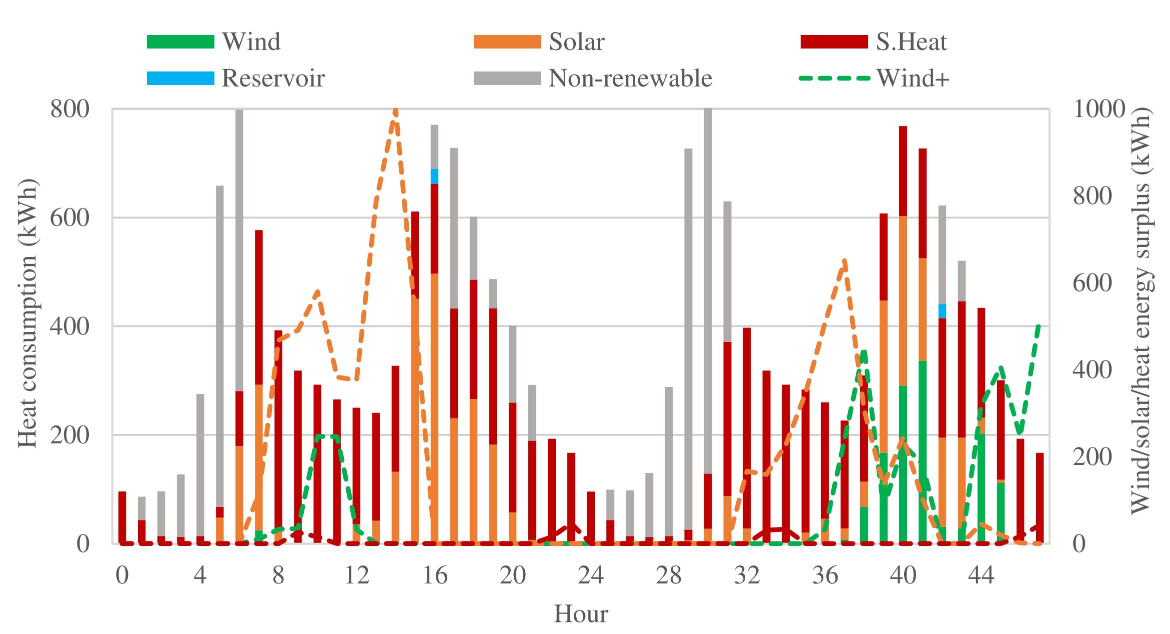

Figure 4: The supply proportion and surplus from wind/solar/heat on two randomly selected summer days (7-8 Jul, 2018) in Strathclyde. The secondary vertical axis displays the surplus from wind (denoted by $Wind^+$), solar (denoted by $Solar^+$) and sewer heat (denoted by $S.Heat^+$).

In Figures 5 and 6, the hourly surplus generated by the renewable energy mixture, and the hourly renewable energy deficit (e.g. as covered by the non-renewable back-up), are accumulated monthly in order to visualise the size of seasonal surplus and deficit.

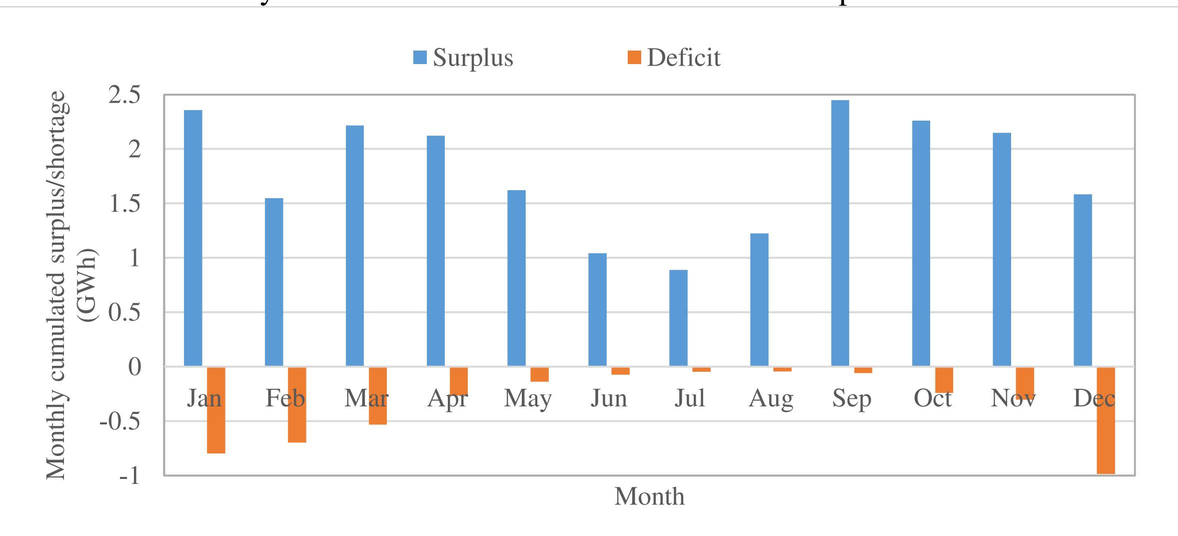

Figure 5: Monthly cumulated energy surpluses/deficits from mixed renewable sources in Strathclyde 2018

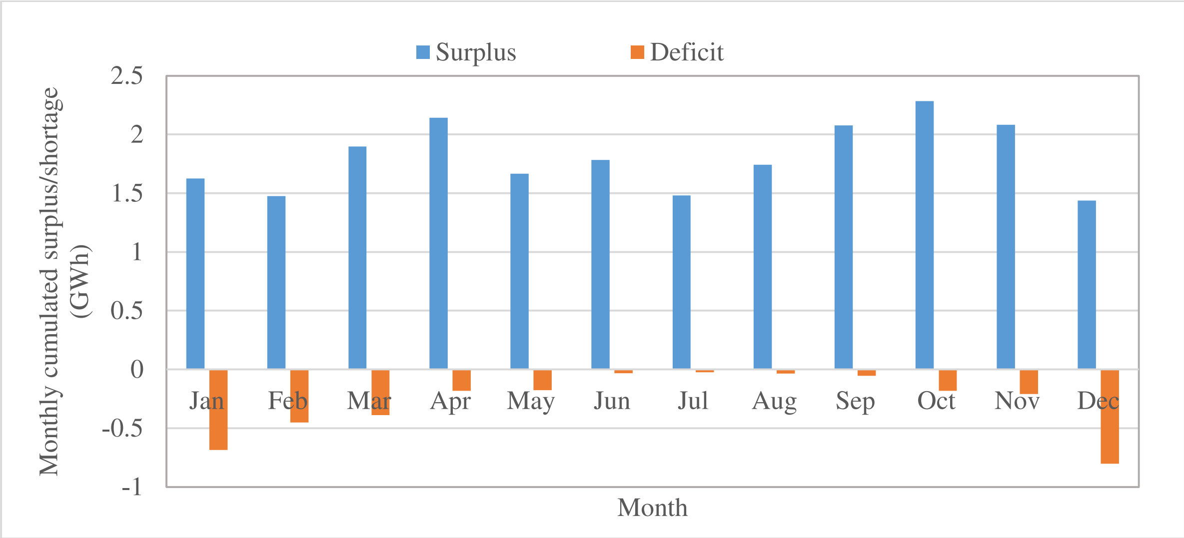

Figure 6: Monthly cumulated energy surpluses/deficits from mixed renewable sources in Gloucestershire 2018

Future Scenarios up to 2035

The results for potential future scenarios of climate, heat demand, and wastewater production (linked with water demand) are shown in Table 4a and 4b. The table shows optimal wind power capacity and solar panel area for the different future scenarios. These are of the same order of magnitude for a wide range of input condition. For all future scenarios tested, a relatively stable carbon emission, and stable percentage of hours that the optimized integrated water energy system is able to satisfy heat demand was found. This indicated that current system performance would be likely to be maintained over the long term.

Table 4a: Simulation results for a range of potential future scenarios (2035) – Gloucestershire (G) and Strathclyde (S), as compared to current baseline (2018)

Scenario		S1	S2	S3	S4	S5	S6	S7
% in hours that satisfy heat demand	S	63%	63%	62%	64%	61%	64%	61%
	G	73%	73%	72%	74%	71%	74%	71%
% in carbon emission reduction	S	47%	49%	47%	50%	47%	50%	47%
	G	56%	58%	56%	59%	56%	59%	56%
Optimal wind turbine power capacity (kW)	S	11861	11430	11982	10476	12560	10478	12624
	G	7532	7334	7598	6994	8008	6993	8031
	S	11106	10888	11989	10281	13460	11363	12158

Optimal solar panel area (m^2)	G	5072	4984	5512	3989	6539	4460	5916

Table 4b: Description of simulated future scenarios

S1	Baseline, 2018 heat demand, wind speed and solar data, and water consumption. Use existing water infrastructure.
S2	3.6% reduction in heat demand
S3	Future water consumption reduces to 115 litres/day/head but service reservoir is fixed at 1200 m
S4	5% increase of both wind speed and solar radiation, 3.6% reduction in heat demand, average water consumption is 115 litres/day/head
S5	5% decrease of both wind speed and solar radiation, 3.6% reduction in heat demand, average water consumption is 115 litres/day/head
S6	5% increase of wind speed and 5% decrease in solar radiation, 3.6% reduction in heat demand, average water consumption is 115 litres/day/head
S7	5% decrease of both wind speed and 5% increase in solar radiation, 3.6% reduction in heat demand, average water consumption is 115 litres/day/head

Discussion

The 2018 baseline shows that a linked water-energy system at a community level is able to deliver a considerable carbon emission reduction (47% in Strathclyde and 56% in Gloucestershire relative to the current 2018 levels, compared to the domestic heat demand still being primarily met by natural gas. The simulations associated with future scenarios indicated that even under anticipated long-term changes, such a linked water-energy system would still be able to deliver a similar level and an additional carbon emission reduction of up to 3% against the 2018 baseline. More may be possible if an energy storage system would be installed.

Among all the simulations, the required solar panel area is estimated to be between 4 and 12 m^2 of roof area per household, which seems feasible.

In all 'current–2016/2017/2018' scenarios, and at all locations a common temporal pattern of system behavior was observed. During the winter, even with the storage/recovery capacity of the drinking water reservoir added, there is often surplus wind power for a number of hours each day. In the summer, there is surplus from both wind and solar energy source for the majority of hours, this is because summer demand is low and this can often be met by sewer heat alone.

Sewer heat recovery can form a considerable additional source of renewable energy in summer, especially when limited wind or sun is available. It is able to cover the whole domestic heat demand for several hours each day.

The optimal solutions for the future 2035 scenarios tested are relatively insensitive to the currently projected changes in heat demand, climate change and future water consumption. The number of hours that the integrated system could satisfy heat demand in 2035 is similar to the current day scenario, thus between 26 to 39% of hours a non-renewable back-up source is needed during winter and summer. Soil energy storage and recovery is currently estimated to be around 22% efficient (Jradi et al., 2017). The annual energy surplus estimated by accumulating the monthly surpluses shown in Figure 5 is approximately 21 GWh for Strathclyde so a total of 4.6 GWh may be available if long term heat storage and recovery in the soil of 22% efficiency is indeed feasible. This is sufficient to cover the sum of the monthly deficits over the year (estimated to be 4.2 GWh), from the monthly values shown in Figure 5. For Gloucestershire, total annual energy surplus in Figure 6 is almost 22 GWh, and so up to 4.8 GWh of effective in-soil heat storage is potentially available. The total cumulated deficit at this site was estimated to be 3.2 GWh. So the use of existing methods to store heat over seasonal timescales in the soil would ensure that such an integrated system would be able to satisfy demand using only renewable sources. Therefore, to achieve zero emission domestic heating through a local system of renewable energy generation integrated with the water system, there is the need to develop and deploy local energy storage at both a daily and seasonal timescale.

The emerging field of coupling ground source heat recovery and sustainable drainage systems or urban surface water (Rey-Mahía et al., 2019; Ali et al., 2017; De Graaf, 2008) would be an additional interesting avenue to explore how linking urban water systems can further enhance the potential for the delivery of carbon-free domestic heating in the UK. De Graaf et al. (2008) considered an urban area of 2816 houses and concluded that by cooling the surface water with 1.5-1.6 °C during three months in summer, an aquifer thermal energy storage supplemented by surface water heat collection (ATES+) has enough heat to satisfy full residential heating demand.

A major benefit of this type of local integration is that it does not require strengthening of either the local distribution electricity network or the national transmission network. The peak PV production in this study is a small proportion of the capacity (5-10%) on a typical local distribution network in the UK, and there should not be any operational issues (Navarro-Espinosa and Ochoa, 2016). The wind turbine is expected to connect to the substation directly, with a maximum production around 10 MW, this would be easily manageable in the majority of cases (Northern Powergrid, 2019).

Conclusions

By implementing the combined energy-water system described in this paper, carbon emissions could be reduced by 47-56% for application at the scale of a community of 1000 households. Without storage the system is expected to satisfy heat demand using renewable energy for around 61-74% of time. Simulations were carried out using two distinct areas in the UK to examine the influence of regional location and future scenarios of changing demand and climate. Whilst some variance was observed it was considered that the values of CO_2 reduction and replacement of non-renewable energy with renewable energy was representative of locations in mainland UK and robust to the future scenarios explored.

The estimated amount of time that a non-renewable back-up source is still necessary proved to be relatively insensitive to the variation of the future scenarios tested. But this analysis demonstrated that it would be necessary to combine seasonal and daily heat storage into such an integrated system in order for non-renewable sources of energy to be fully replaced. By looking at the duration and magnitude of non-renewable input, one can estimate that for Gloucestershire in 2018 the required storage power capacity would be 341 kW per household, whereas for Strathclyde in 2018 it would be 162 kW per household.

In terms of the investment required for a localized integrated water-energy system, the levelized cost of electricity from solar PV and onshore wind have fallen significantly over the last decade. It has been shown that a single building-mounted wind turbine can supply about 40% of the annual energy demand of a single domestic household (Gagliano et al., 2013). A PV single building thermal system could provide 51% on an individual household electrical demand coverage (compared to an equivalent PV-only value of 49%), plus a 36% coverage of hot water demand (Herrando and Markides, 2016) so combining these technologies at a community scale can offer even higher levels of contribution from renewable sources, more reliable coverage and higher carbon emission reductions than if these technologies were deployed individually. The capacity of the wind power generation required for a 1000 household community is of a scale that local distribution networks would not need to be significantly strengthened. Therefore, community scale systems could be progressively adopted with more limited investment compared to the national level transmission enhancement envisaged by the widespread use of offshore wind energy.

The use of small scale community based integration, also requires less investment than in larger capital intensive heat networks currently being proposed for dense urban centers in the UK. Integration at a community scale also ensures that existing electricity distribution networks can usually cope with the additional load caused by modest use of onshore wind generators, thus deferring significant investment in the local distribution and national electricity transmission network that is currently being implemented and planned.

To achieve additional carbon emission reduction for domestic heating, such a community based integrated system would need to be combined with both daily and seasonal energy storage, enabled by existing heat storage technologies given that future wind speed and solar radiation levels in the UK are currently not predicted to change significantly over the next few decades.

In the UK, not all households in a community would be close enough to a large enough sewer to enable practical sewer heat recovery. The spatial limitations of sewer heat recovery are not explored by the analysis described in this paper and further/more detailed research, based on a case study approach would be needed to spatially optimize the recovery of heat energy from this non-renewable source.

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