Renewable Energy Technologies in Campus-Sized Developments: A Spatial Study

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Abstract

Using hourly energy and water consumption data and theoretical models representing low-carbon and green energy production technologies, such as photovoltaic panels, wind turbines, combined heat and power, solar collectors, and seasonal thermal energy storage, an integrated node-based static model has been developed. Assembled in MATLAB and Simulink, and based on an integrated resource management approach, it reproduces annual hourly energy consumption and production values for hypothetical campus-sized developments with onsite energy generation. For three configurations of generation technologies, results are then presented from simulations exploring the spatial characteristic and requirements of the development. Also, the article concludes that alteration in the composition of the technologies used has significant spatial impact and implications on achieving carbon-neutral developments.

Keywords Energy Modelling, Low-carbon Developments, Renewable Technologies, MATLAB Simulink

1.0 Introduction

European Union's Climate Action calls for a 20% reduction in carbon levels from the 1990 emissions by year 2020 (1). Achieving this target would require extensive measures to be taken in variety of sectors. In the United Kingdom, built-environment has been identified to be responsible for a third of the total carbon emissions (2). This, therefore, portrays a potential for substantial carbon reductions in this sector. Over the past couple of decades a variety of technologies have been developed for low-carbon and renewable production of energy including PV, solar collectors, wind, etc. The delocalized system of these technologies could be used for the purposes of reducing carbon emissions in developments of certain sizes.
This study will then explore the spatial implications of supplying the demand of an idealized campus sized development solely through the use of low carbon and renewable technologies.

1.1 Why Campus?

Campus developments provide for an ideal scale in terms of energy management due to the limited number of stakeholders involved in the processes of construction and management. In addition the autonomy of the stakeholders to control the unit independently make the realization of developmental targets more expedient and feasible.
Furthermore, campuses by nature allow for a presence of a mixture of typologies. This results in aggregated demand profile less sensitive to the particularities of individual typologies providing for wider options of supply technologies. This effect has been illustrated by the study done by ARUP San Francisco (3). Figure 1 shows the optimal scales for a few supply services. It can be noted that a good majority of services optimize on campus level.

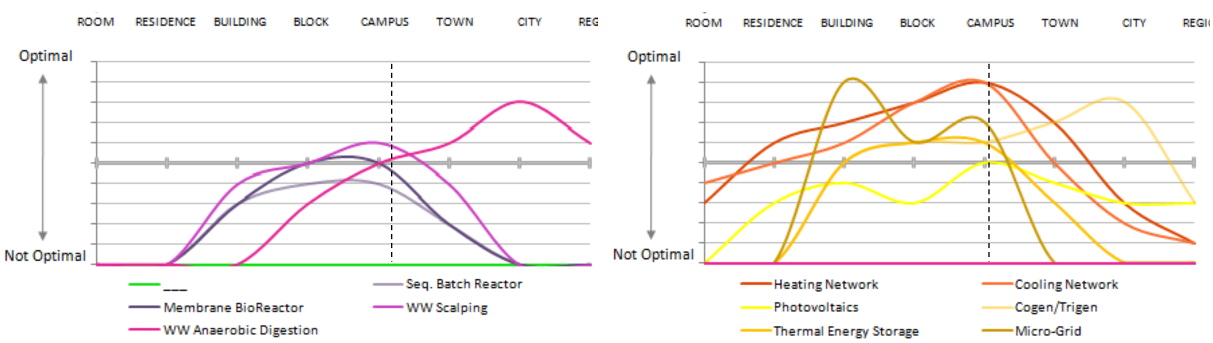

Figure 1 Optimal system scale for energy and water, courtesy of ARUP San Francisco

1.2 Existing Software

Currently, there are a few software packages capable of running energy supply and demand analysis on a variety of scales for different technologies. A brief overview of a number of these packages consulted for the purposes of this study is presented in Table 1. A full review of energy simulation and optimization packages is available by Manfren et al. (4).

Software	Scale	Sectors addressed	Capabilities	Limitations
HOMER (5)	Local	Electricity, Heating and Transportation	Simulation and optimization of supply and demand network	Limited supply technologies, Economy based simulation, Lack of customizable input data capability
TRANSYS (6)	Local	Electricity and Heating	Transient system simulation – HVAC systems and microgeneration	Requires existing building design
EnergyPlus (7)	Local	Electricity and Heating	Building energy simulation model	-
UWOT (8)	Building	Water and Grey water	Building water system simulation	Lack of maintenance and support
MLE+ (9)	Building	building automation design, co-simulation and analysis	Building Energy Simulation	Most efficient in conjunction with EnergyPlus

Table 1 Current energy analysis packages and their capabilities

2.0 Methodology

A model has been set up using MATLAB Simulink to allow for time series analysis of energy demand and supply for a campus development over the course of a year in hourly increments. This has been done generating hourly consumption values for residential and office typologies considering electricity, heating, and water demand. The generated demand is then supplied for by connection with production nodes which simulate power output of several technologies using environmental data. Figure 3 portrays a snapshot of scenario configured within Simulink.

For this analysis, the national grid has been assumed to act as an on-demand storage eliminating the need to model onsite storage technologies. As such, at every hour, the generated supply on times of low demand is stored into the 'grid' and used later in times of resource unavailability.

The model has been assembled mostly to examine the spatial implications of using such generation technologies and hence is only concerned with the operational carbon produced over a year. These are then translated in terms of equivalent spatial requirements and compared for a number of technology configurations. The following section describes the inner workings of each node:

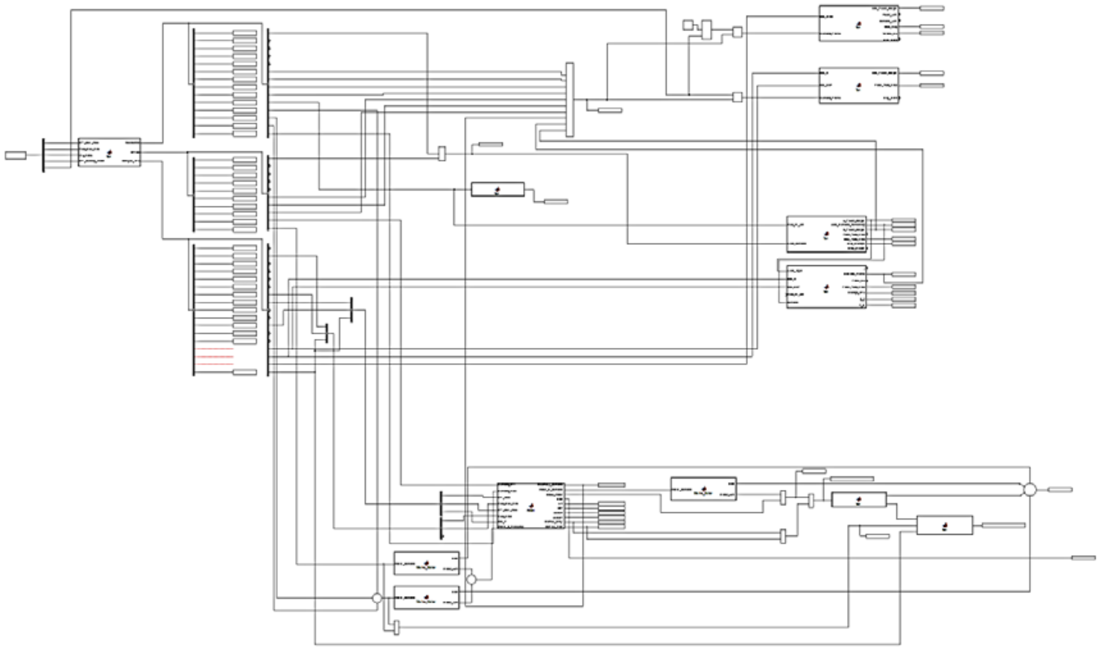

Figure 2 Snapshot of the model showing different nodes and flows

2.1 Model Configuration

2.1.1 Input Data

Environmental: to describe the environmental characteristics of the site, Prometheus probabilistic climate change data (10) has been used to determine the hourly values for wind direction and speed, solar irradiance and dry-bulb temperature. The simulation utilizes the projected values for a Test Reference Year (TRY) corresponding to weather condition in year 2050 under medium emission scenario A1B (11).
The National Renewable Energy Laboratory's solar position algorithm for solar radiation applications (12) is used to obtain the hourly solar azimuth and elevation throughout the year.
Heat gains: due to occupants activity and appliances for each building typology have been estimated. For residential, a weekly profile has been constructed using hourly values corresponding to a typical household of two adults under 65 over weekdays and holidays, see Patterns of Residential Occupancy (13) for a detailed description of the monitoring process. The internal gains for the office typology, however, has been put together using recorded occupancy characteristics and consumptions of Hugh Aston Building (14) and ASHRAE heat gain benchmarks for people and workstations (15).
Electricity: consumption profile for each typology has been set up separately. residential annual profile has been constructed using data for workdays and holidays, available from Household Electricity Survey (16), scaled based on the total annual consumption of a development of BedZED characteristics (17) approximating better practices. The office electricity usage was estimated based on recorded values from Hugh Aston Building (14) adjusted per person based on source building number of occupants and broken down by usage category (18). Figure 4 illustrates sample residential electricity demand generated for 20000 residents over a week.

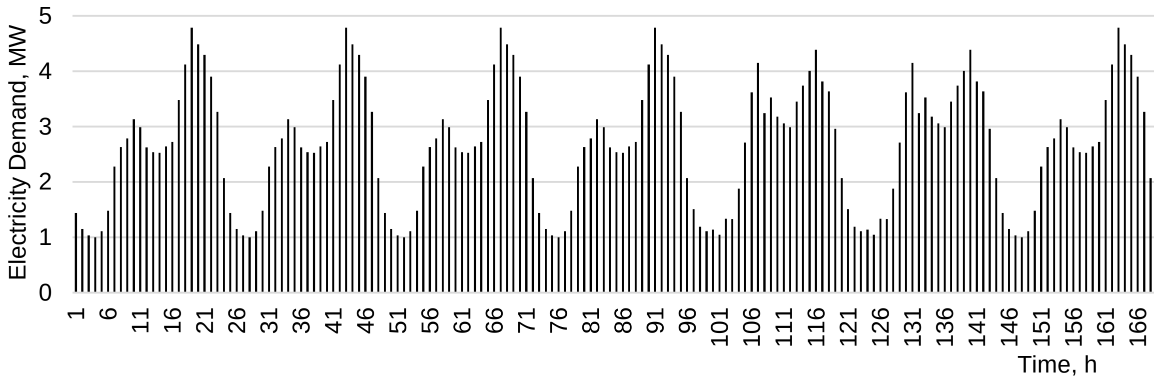

Figure 3 Sample residential electricity demand of 20000 residents for a week starting on Tuesday

Domestic Hot Water: consumption profile and common feed and boiler temperatures for residential typology were adopted from average month specific daily profiles in the Measurement of Domestic Hot Water Consumption in Dwellings report (19) adjusted for the number of occupants per household.

Water*:* for precipitation and collected rain water, hourly data recorded by Met Office for the year 2013 in the town of Thorncliffe has been used (20).
Residential demand has been constructed by the hourly consumption profile scaled by BedZED's overall water demand. For further details see House (21) and Hodge (22). For office water demand, however, detailed data broken down by usage could not be sourced. As a base for creating the demand profile, the overall hourly consumption of water recorded during 2013 for the Hugh Aston Building (built in 2009) in Leicester was used (14). Based on the Gross Internal Area (23) of the building and an average of 11 m^2 (24) a demand profile per person has been obtained. Finally, based on the overall average ratio of water consumption (30% potable and 70% grey water), an assumption was made to split the hourly values using the same ratio (25). A sample residential water demand constructed for 20000 residents is shown in Figure 4 over a day.

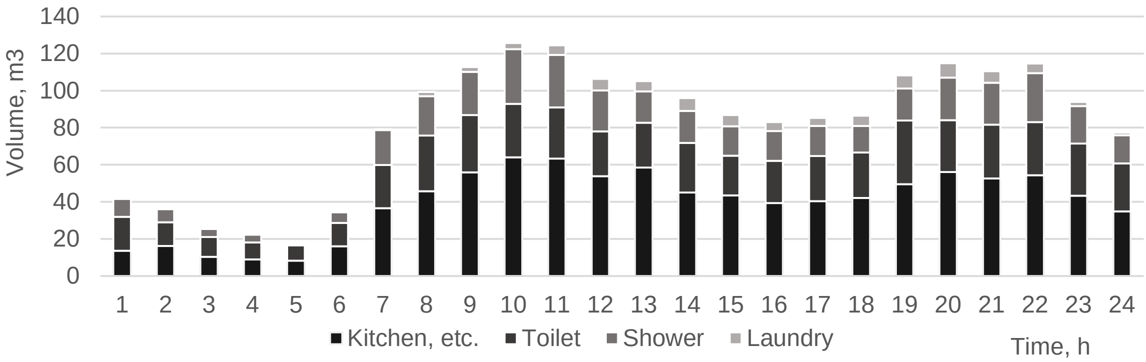

Figure 4 Sample hourly water demand generated for 20000 residents over a day

2.1.2 Campus Simulator

The node is used to generate and define campus overall demand and geometry for different values of total number of residents, rise of residential development, total number of employees, rise of office development, building width-to-length ratio, and total number of office buildings set prior to the simulation. For office buildings this is done according to pre-set building widths and width-to-length ratios while the residential geometry is simplified to cubic units corresponding to the number of households and residents.
The node produces electricity and heating demand profiles for each typology using the input data under the following assumptions:

- 20 m^2 of residential area per resident and 11 m^2 of office area per employee
- stable internal temperature set at 17^{o}C and 21^{o}C for residential and office typologies respectively.
- uniform envelope U-value of 0.11 W/m2K
- ventilation rates of 1ACH
- steady-state heat transfer only through fabric
- heat gains and losses are calculated for every hour for that hour alone
- 35% glazing and a shading correction value of 0.97 and 0.57 for winter and summer respectively

As such, the heating demand of each typology is calculated considering the hourly steady-state heat transfer comprised of fabric and ventilation heat losses and internal and solar gains through the glazing discarding other radiative losses of fabric surface.

2.1.3 PV panels

A simplified PVFORM model (26) with fewer specified inputs is used to estimate hourly outputs for particular sets of panel tilt and azimuth, total number of panels, maximum output, width and length, reference temperature and reduction factor provided in advance. The node utilizes:

$$Pmp = \frac{E}{1000} \cdot Pmp_0 \cdot [1 + \gamma \cdot (T - T_0)] \quad (1)$$

where Pmp_0 is the maximum power output, E, the plane-of-array irradiance, γ, the power reduction factor, T and T_0, the external and reference temperature respectively. For a detailed description of the method used see (27) and (28).
for each hour, the corresponding value of E is calculated according to equations two to five.

$$E = E_b + E_g + E_d \quad (2)$$

where E_b, E_g, and E_d represent plane-of-array direct, ground reflected and sky diffuse irradiance components respectively. These are calculated at each step using Prometheus projected environmental values (10):

$$E_b = DNI \cdot \cos(angle\ of\ incident) \quad (3)$$

where *DNI* is the direct normal irradiance and angle of incident is calculated as per NREL algorithm (12).

$$E_g = GHI \cdot albedo \cdot \frac{[1 - \cos(panel\ tilt)]}{2} \quad (4)$$

where *GHI* is the global horizontal irradiance and panel tilt specified based on node inputs. An albedo value of 0.2 has been used to represent urban environments (29).

$$E_d = DHI \cdot \frac{[1 + \cos(panel\ tilt)]}{2} \quad (5)$$

where *DHI* is the diffuse horizontal irradiance. For a more detailed explanation of the approach see (30).
Finally, the node utilizes the input demand profile and the annual simulated power output to estimated total required area to meet demand.

2.1.4 Wind Turbines

The node takes use of several power curves compiled for different models of various output and rotor diameter (31) to estimate hourly power outputs for selected models. Wind speed data obtained from the Prometheus dataset are adjusted for appropriate turbine height according to:

$$\frac{U}{U_0} = (\frac{h}{h_0})^{\alpha} \quad (6)$$

where U_0 and h_0 represent the projected wind velocity and height from Prometheus, U modified velocity for turbine height of h and α taken as 0.25 for a terrain of rough surface (32). The node takes a pre-set farm orientation and assumes functioning turbine output for a wind direction of up to 10% deviation.
Similar to the PV Panels node, the number of required turbines to meet the input demand is calculated and used to estimate the area required for the farm assuming a 3 to 10 turbine diameter spacing.

2.1.5 Solar Collectors

Figure 5 shows a simple schematic of the system modelled within the node. In every hour the collector gain is estimated using the following for all positive outputs:

$$q_C = A_C F_r [I_t \eta_0 - U_L (T_{Ci} - T_{DBT})]^+ \qquad (7)$$

where A_C is the Collector surface area, I_t is the radiation intensity on the collector and calculated using the same algorithm as the PV Panel node, η_0 the collector's optical efficiency, U_L the collector's overall heatloss coefficient, T_{Ci} and T_{DBT} inlet fluid and external dry bulb temperatures respectively, and F_r the heat removal factor which is calculated as per equation eight (32). However, for simplicity, T_S, storage tank fluid temperature, is used to replace inlet fluid temperature in equation seven.

$$F_r = \frac{m_C c_{pc}}{A_C F' U_L}\left[1 - \exp\left(-\frac{A_C U_L F'}{m_C c_{pc}}\right)\right] \qquad (8)$$

with c_{pc} representing the fluid's specific heat and F' the plate efficiency factor provided by manufacturers.
Environmental losses of the storage tank are simply estimated according to:

$$q_w = U_S A_S (T_S - T_{DBT}) \qquad (9)$$

with A_S and U_S representing storage tank surface area and heatloss coefficient respectively. For practical purposes in simulation, the external dry bulb temperature is replaced with a constant ground temperature of 8 ºC for every hour.
Maximum available output based on storage temperature and required outlet temperature whether domestic hot water, assumed 15 ºC, or heating, assumed 35 ºC, is then calculated assuming that all heat exchangers in the system have efficiencies of 100%. Hourly demand profiles are then used to estimate required auxiliary heating if needed.

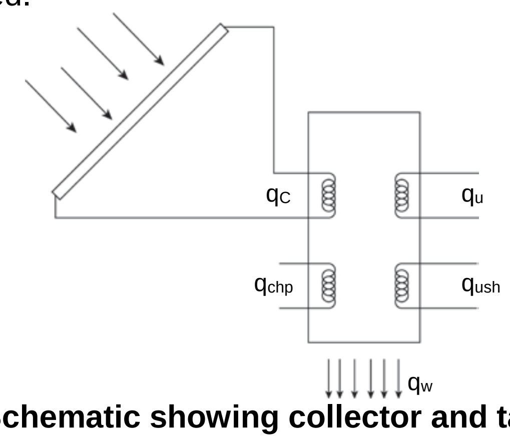

Figure 5 Schematic showing collector and tank setup

At the end of each hour the node recalculates storage temperature is calculated:

$$T_S(t) = T_S(t-1) + \frac{q_C(t)\ [+q_{chp}(t)] - q_u(t)[-q_{ush}(t)] - q_w(t)}{M_S Cp_S} \qquad (10)$$

where q_C, q_{chp}, q_u, q_{ush}, and q_w represent heat input from collectors and combined heat and power (CHP) plant and heat output for domestic hot water, space heating and environmental losses for the time increment *t*. Brackets represent values the inclusion of which depends on the configuration of the node with respect to the others.
The node simulates a system of flat collectors and seasonal thermal energy storage tank operating with water for a range of farm areas and tank sizes specified prior to the simulation to meet a target solar fraction in order to find the smallest farm size in the range corresponding to the target solar fraction.

2.1.6 Combined Heat and Power

The median of the heating demand is used to set the heating output of the plant. For the purpose of the simulations considered here, the plant is assumed to have a heat-to-electricity ratio of 2 and an overall efficiency of 80%. The crop area required is estimated for crops of miscanthus based on crop net dry calorific value of 17 MJ/kg and average crop yield of 0.1 kg/m2. For detailed information on miscanthus growth and management see Defra's Best Practice Guidelines (33). It should be noted that the node does not consider the size of the plant itself and only estimated the crop area required. The node also produce hourly outputs for the portion of the electricity generated and the heating demand profile left to be supplied.

2.1.7 Rainwater and grey water collection

Overall three types of water were considered according to (34):

- Potable Water – water supplied for all uses apart from toilet flushing
- Grey Water - wastewater excluding faecal matter and urine (water from laundry, kitchens, bathrooms and taps)
- Black Water – wastewater with faecal matter and urine

The collected rainwater is calculated using the following:

$$Q = A \cdot e \cdot P \qquad (11)$$

where *A* is the roof area of the building, *e* is the yield coefficient (0.8 for flat roof without gravel (34)), and *P* is the precipitation in each hour.
The overall logic of the node is to give priority to the water from precipitation, addressing the demand with the available for the hour rainwater and storing the excess in a tank which is also used for storing grey water. In the case of unsufficient rainwater, water from the tank is pumped to the point of use. A design decision was made that the tanks would be sized in order to provide water for 24 hours based on the mean hourly demand over a year and that they would be full initially. For the demand addressed with rainwater a gravity-fed system is considered, while for water extracted from the tank a corresponding electricity demand for pumping is calculated using the following equation:

$$Q = \frac{Q_s \cdot \mathrm{h} \cdot g}{e} \quad (12)$$

where Q_s is the supplied water, *h* is the floor to floor height, *g* is the earth's acceleration and *e* is the pump efficiency. For the purpose of this simulation an overall value is assumed as: e = 0.437 based on 0.85 for electric motor, 0.98 for direct drive mechanical transmission, 0.70 pump efficiency, 0.75 hydraulic losses (35).

Two interconnected tanks are considered for the residential and the office buildings, with the excess water directed to the other tank. The hourly simulation of the tanks is based on the algorithm by Mun and Han (36) following the algorithm shown on Figure 7 where V_t is the volume of water in the tank; D_t – demand of water; Q_r – rain water supply; Q_g – grey water supply.

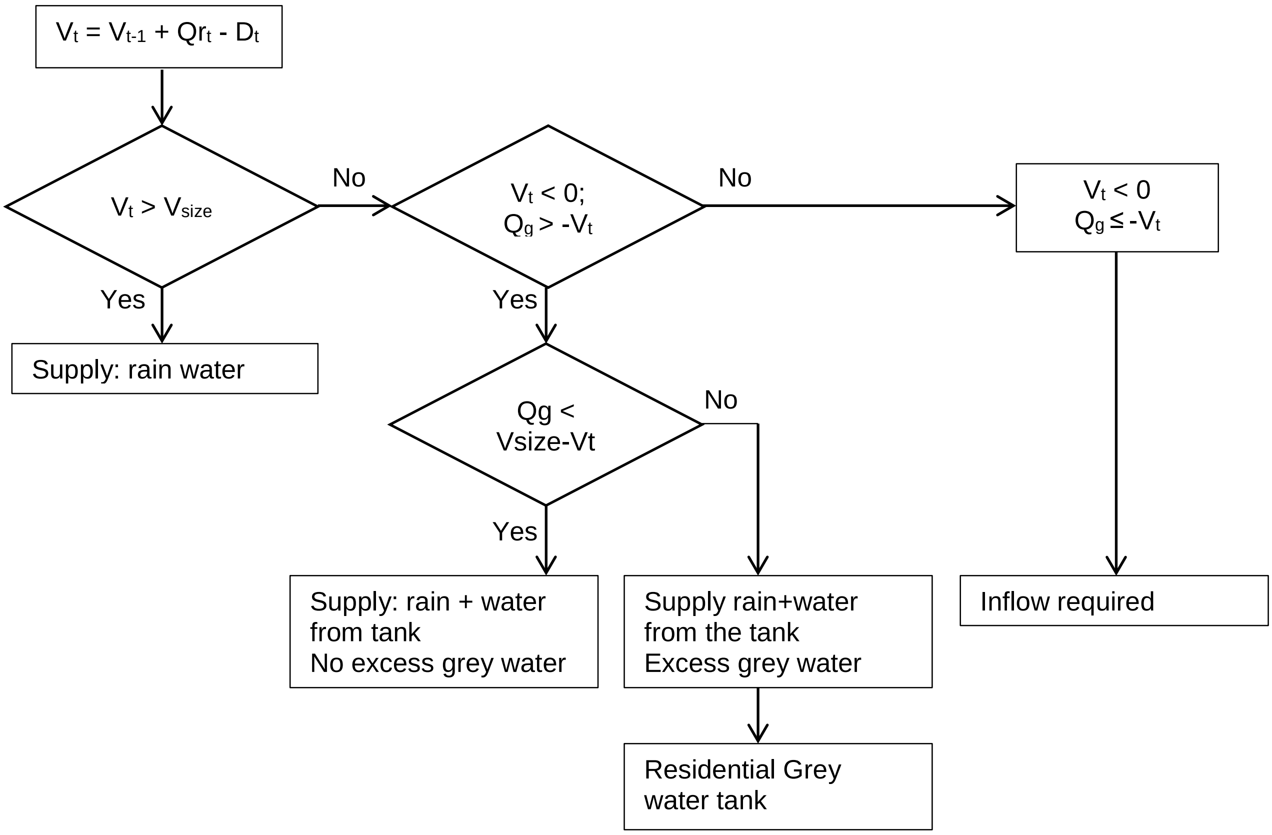

Figure 6 Flow Chart of the tank simulator

2.1.8 Mains Water

Considered in terms of its associated carbon equivalent (0.3441 kgCO2e/m3) using the carbon conversion factors by Defra's spreadsheet (37). For determining the resulting grey water after satisfying the demand, total losses of 30% are considered.

2.1.9 Water Treatment

A campus size waste water treatment plant (WWTP) is considered. Best practice wastewater treatment plants generate electricity from methane extracted from the waste. Based on the energy efficiency of Werdhötzli, Sweden (100%) and Strass, Austria (108%) it is assumed that the plant will be self-sufficient. (38). The operational carbon produced by burning methane obtained using the enthalpies of formation following equation (#) scaled by a factor of # and using energy intensity for of 505Wh per cubic meter of waste water and the amount of carbon (38).

$$CH_4 + 2\,O_2 = 2H_2O + CO_2 \qquad (13)$$

Water losses of 30% are assumed during the treatment process.

2.1.10 Additional Rainwater Collection

In this node, the amount of treated water from the WWTP is subtracted from the initial intake from mains water and a required additional area for rainwater collection is determined. A lower yield coefficient of 0.6 from green roof designs is considered based on (34).

3.0 Simulation Configuration

For the purposes of this paper, three different scenarios corresponding to three configurations of the nodes discussed previously have been set up. These have been chosen prioritising the order in which the nodes address electricity, heating and water demands. Table 2 and Table 3 show the range of input assumptions considered for the campus node and design parameters used for technology nodes common to all three scenarios.

	Residential	Office
Number of Occupants (persons)	20000	10000
Designate Area per Person (m^2)	20	11
Occupancy Time (weekdays)	18:00 – 09:00	09:00 – 18:00
Rise of Development (stories)	1-3	1-3
Width to Length Ratio	1	0.5, 1, 1.5
Geometry	Square plan	Rectangular plan
Input width (m)	8.4*	7, 14, 21

* based on an assumption of 3.5 members per family

Table 2 Input assumption for campus node

Node	Parameters					
Wind Turbine	Diameter (m)	Orientation (degrees from north)	Unit Power (MW)	Capacity (MW)	Cut-Off Velocity (m/s)	
	60	240	1.3	183	25	
PV Panel	Unit Area (m^2)	Tilt (degrees)	Orientation (degrees from north)	Max Power Output (W)	Power Reduction Factor (K^{-1})	
	1.25	40	180	240	0.0038	
Solar Collector	Unit Area (m^2)	Tilt (degrees)	Orientation (degrees from north)	Solar Fraction	Optical Efficiency	Heatloss Coefficient (W/m^2K)
	2.15	40	180	0.7	0.81	3.97

Table 3 Input parameters used for technology nodes

3.1 Base Scenario

In this scenario all energy demands, i.e. electricity and heating, are provided for using the PV Panel and Wind Turbine nodes. Different iterations of the scenario are considered for the various composition of these technologies, Table 4. The model also addresses the demand for potable water with mains water and feeds the resultant grey water to a collection tank. An integrated rain and grey water collection system, then, supplies both the residential and office buildings with water for toilet

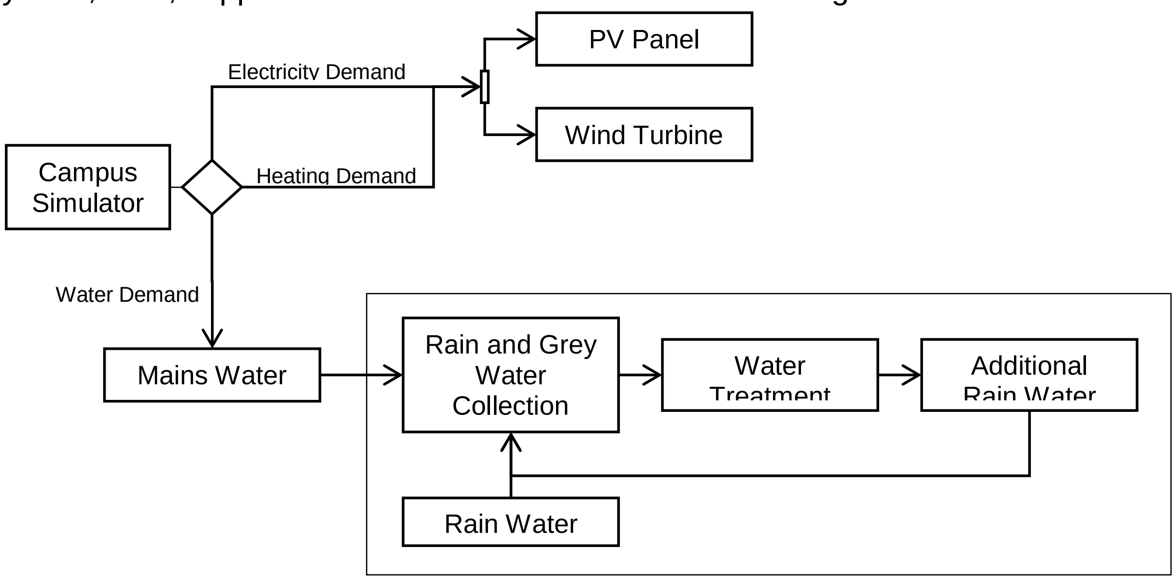

Figure 7 Schematic of base scenario showing node connectivity and flow

flushing. This is then passed on as black water to the WWTP. Figure 8 illustrates an overall schematic of the scenario configuration with the energy and water demand flows indicated.

Iteration	Technology Demand Share (%)	
	PV Panel	Wind Turbine
1	0	100
2	20	80
3	40	60
4	60	40
5	80	20
6	100	0

Table 4 Demand share used for different iterations within each scenario

3.2 Seasonal Thermal Energy Storage (STES) Scenario

For this scenario, it is assumed that heating demand are first addressed through the Solar Collector node to size the farm required to meet the target 70% solar fraction. Afterwards, the remaining heating demand together with the electricity demand is configured through PV Panel and Wind Turbine nodes with similar compositions to that of the base scenario. As shown in Figure 9, the water nodes are configured similar to base scenario.

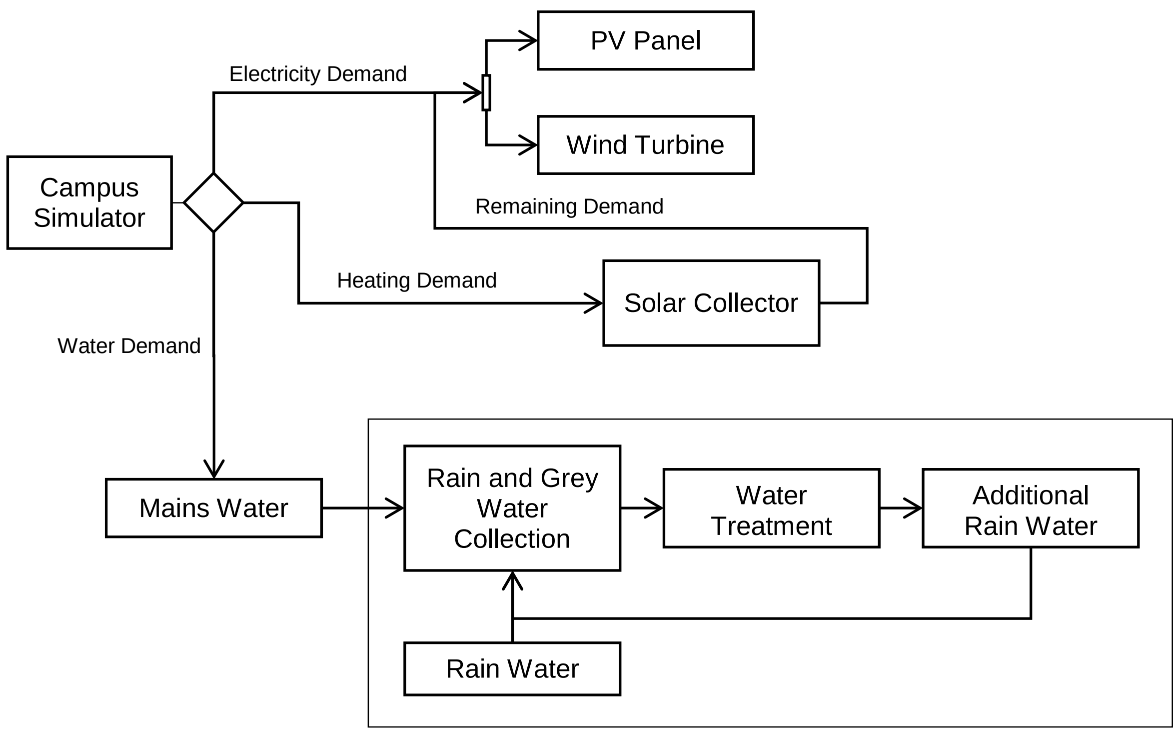

Figure 8 Schematic of STES scenario showing nodal connections

3.3 CHP and STES Scenario

The CHP node is introduced coupled with the Solar Collector node to address the base heating demand and charge the storage tank in times of lower demand. The electricity output of the CHP node is also subtracted from the combined demand to be addressed by the PV Panel and Wind Turbine nodes, Figure 10. The rest of the configuration functions similar to the previous scenarios.

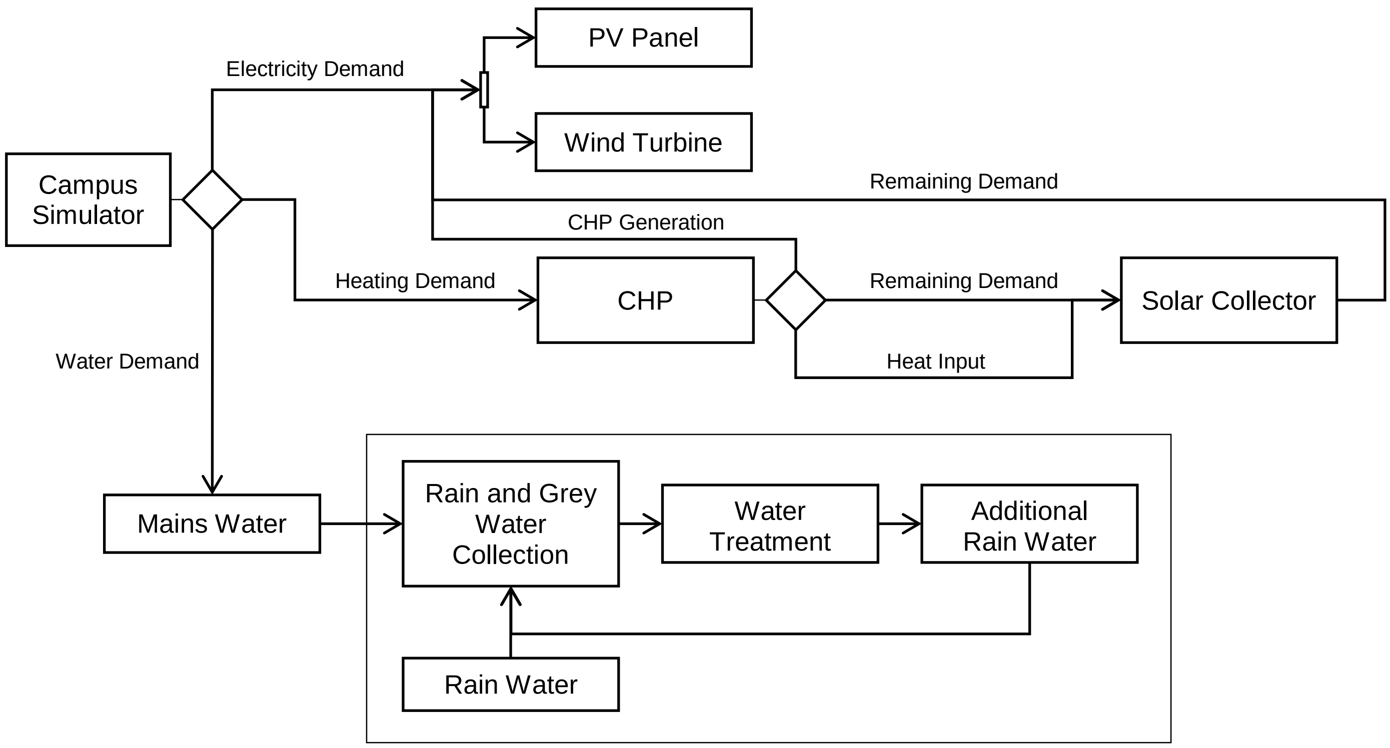

Figure 9 Schematic of CHP scenario showing nodal configuration

4.0 Simulation Output and Analysis

Figure 10 shows consecutive runs of the base scenario for a variable development rise of 1-20 stories for each typology. Each semi-exponential trend, from left to right, denotes overall campus wide annual energy demand corresponding to increasing rise of office development for a constant residential rise. It can be seen that the effects of denser developments on lowering energy consumption decreases rapidly falling to about 10% drop in energy demand per story for rises of more than 6 stories.

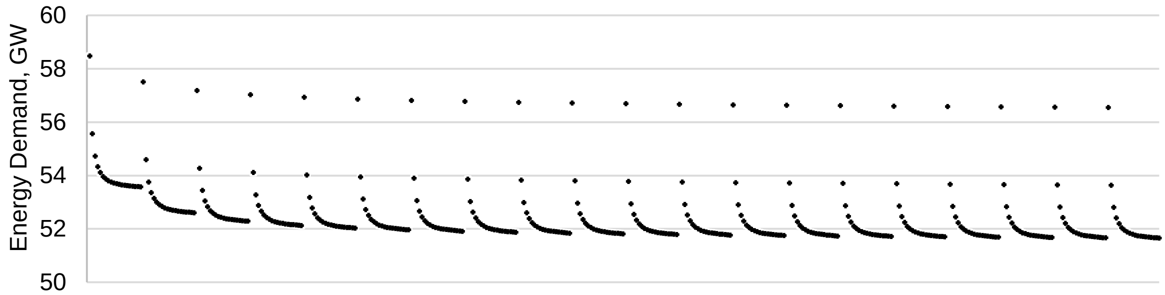

Figure 10 Overall annual energy demand calculated for development rises of 1 to 20 stories. Consecutive trends show energy demand of increasing rises of office development for each residential rise

While the increase in development height does provide for lower energy demands, it may not include consideration regarding construction complications and costs, opportunities for rain water capture, and low energy grey water recycling distribution systems.

For the purposes of the rest of this analysis, the output produced for a development of three stories high in both typologies, with an office building geometry of 21 by 42 meters, will be considered. The choice of width has been made base on the natural ventilation assumption and restriction for non-domestic buildings (39).

For the scenarios introduced, Figure 11 shows electricity, heating, and water demands generated within the Campus Simulator node as discussed previously. It should be noted that the repetitiveness of the residential profile as opposed to that of the residential profile is a result of its composite and constructed nature. Residential heating demand includes both space heating and domestic hot water with the latter comprising the majority of the demand. Some of the roughness in the way the space heating energy demand has been modelled can be justified based on the relative size of electricity demand to that of heating. These include exclusions of considerations for detailed heating controls in each typology or careful accounting of dynamic response of fabric, temperature time lags, and such like.

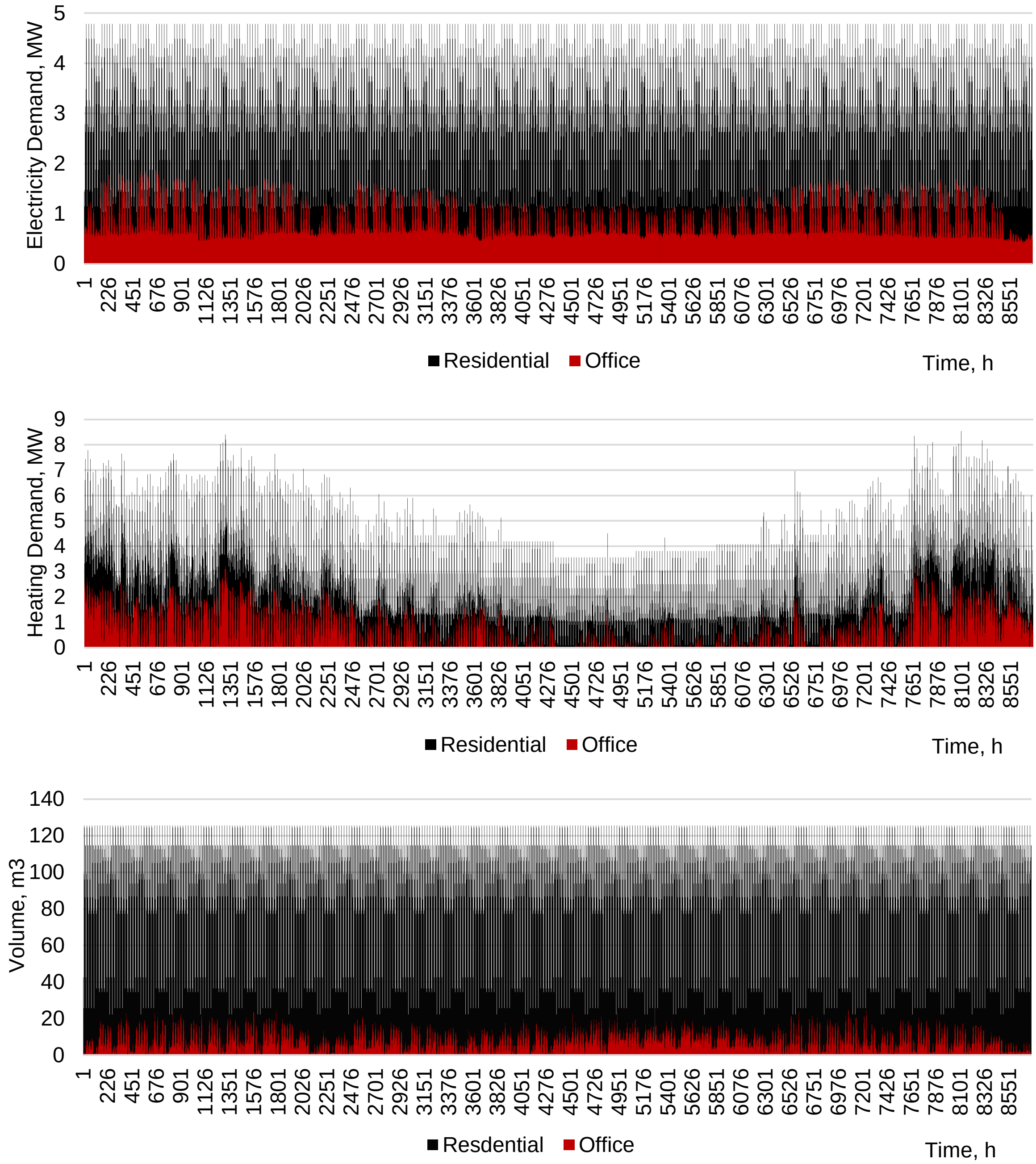

Figure 11 Top: Electricity demand for residential and office development rise of three stories, Middle: Heating demand for office space heating and residential hot water and space heating, Bottom: Water consumption generated for residential and office development rise of three stories [values are not stacked]

The maximum output of production nodes, PV Panel, Wind Turbine, and Solar Collector, for each scenario, is also shown in Figure 12.

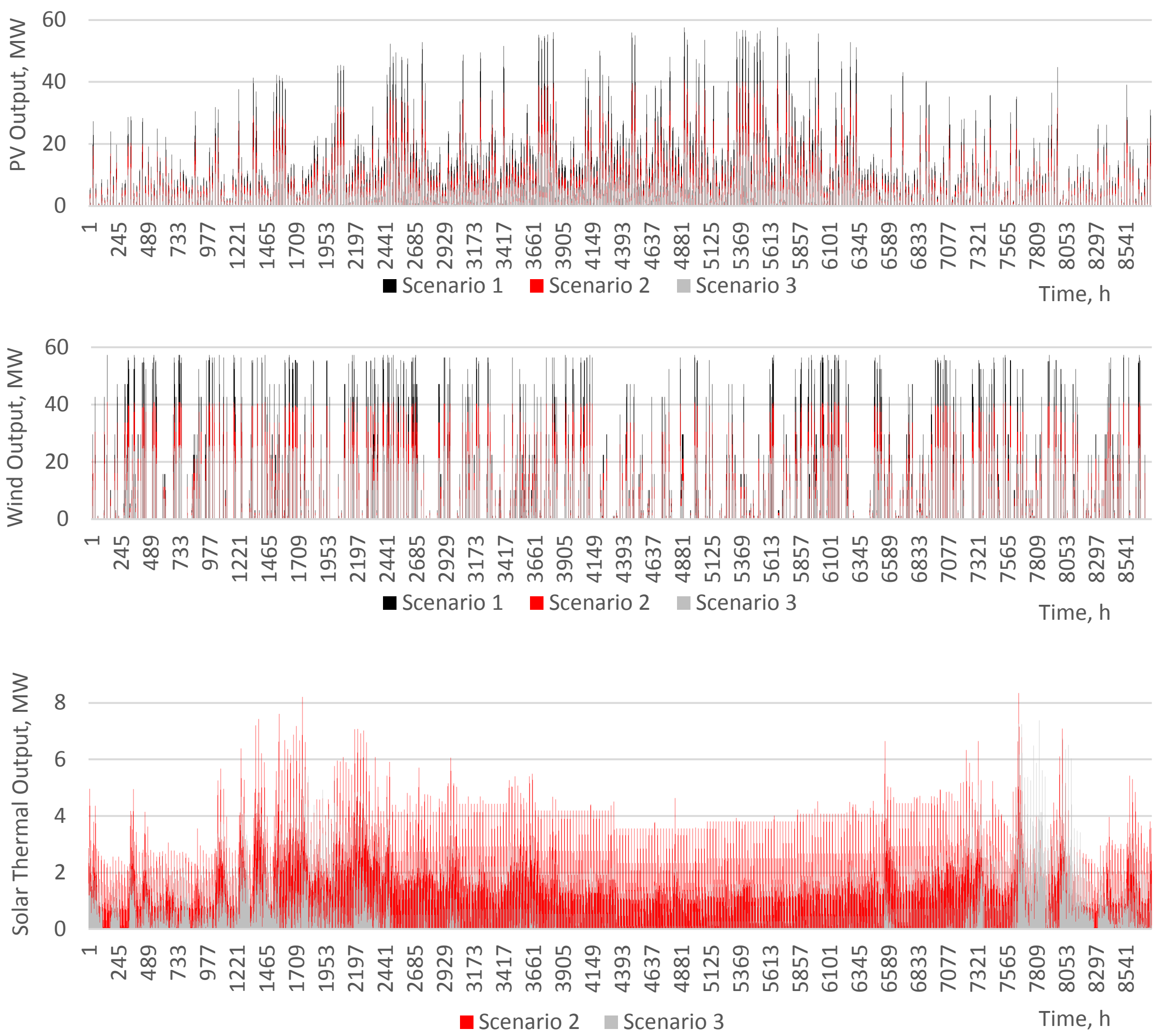

Figure 12 Top: PV output for 100% PV configuration for each scenario, Middle: Wind Turbine output for 100% technology configuration, Bottom: Solar Collector output for target 70% solar fraction.

For each scenario the overall space required for each technology has been estimated. Figure 13 show these estimated areas accompanied by the footprint of the development against a map of Sheffield for better comparison. It is observed that depending on scenario and configuration, to meet campus demand, an area of about 16 to 75 km^2 would be required. The areas corresponding to wind turbines have been estimated conservatively and with large spacing, 10 diameters spacing, considerations. It needs to be noted that realistic estimation of these areas would be dependent on site terrain and topography among other things.

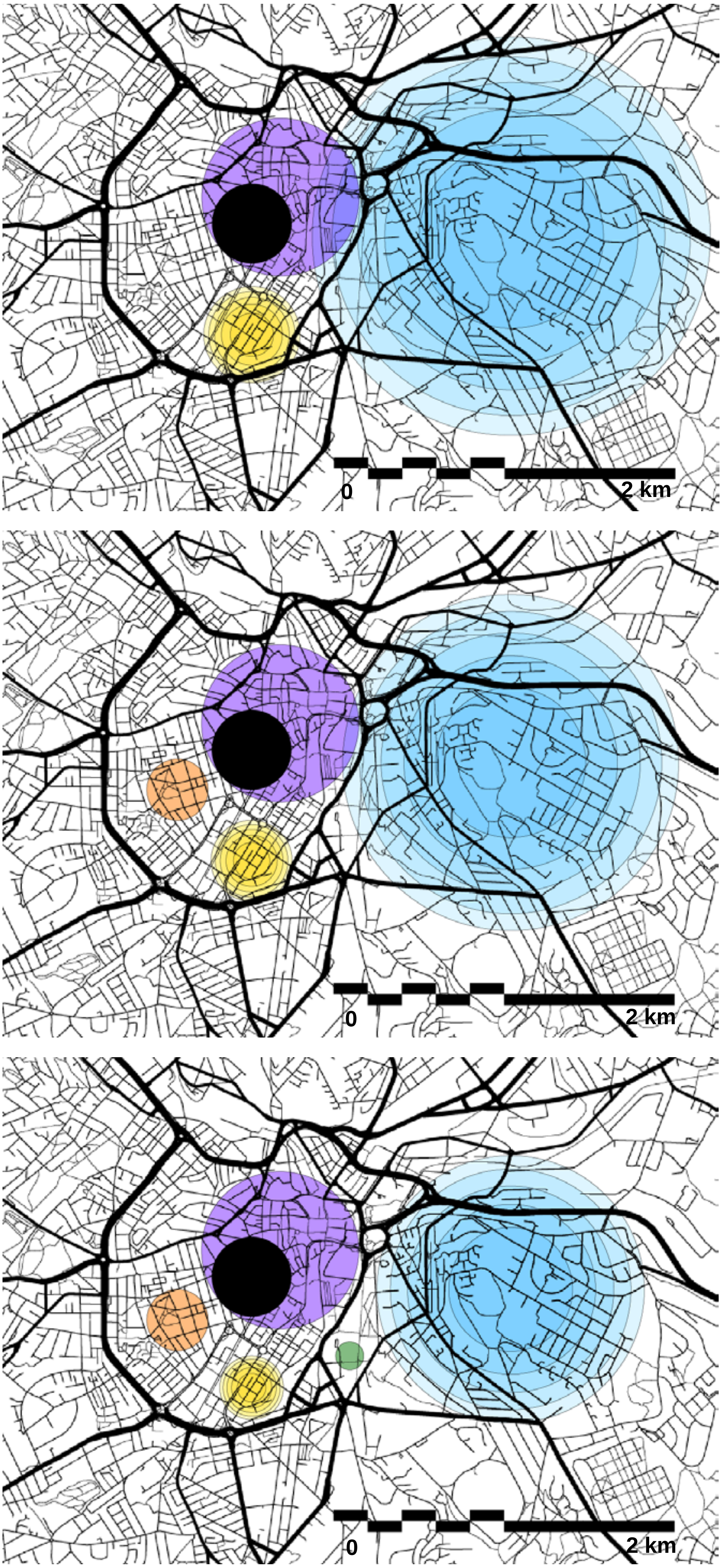

Figure 13 Top: Estimated area for base scenario, Middle: Estimated area for STES scenario, Bottom: Estimated area for CHP scenario – Black for campus footprint, blue for wind turbines, yellow for photovoltaics, orange for solar collectors, green for CHP miscanthus crop, and purple for rain water harvest

As mentioned previously in the methodology, the model has been assembled taking the national grid as a storage on demand. Consequently, to account for the carbon associated with the displaced electricity through the grid as the technology nodes discharge into the grid in times of low demand, an equivalent spatial representation has been considered to capture the spatial implications of grid displacement. Figure 15 shows the equivalent forest area required to offset carbon associated with the grid displaced electricity. This has been obtained using a CO2 emission factor of 0.568 kgCO2/kWh (40) and conversion factor of 2.48 m^2/kgCO2 (41) (42). The immediate issue observed is the effect of technology mix on the carbon associated with the displacement. It could be hypothesized that minority share of photovoltaics provide for more flexible production that enables the overall mix, i.e. turbines and panels, to meet demand more appropriately.

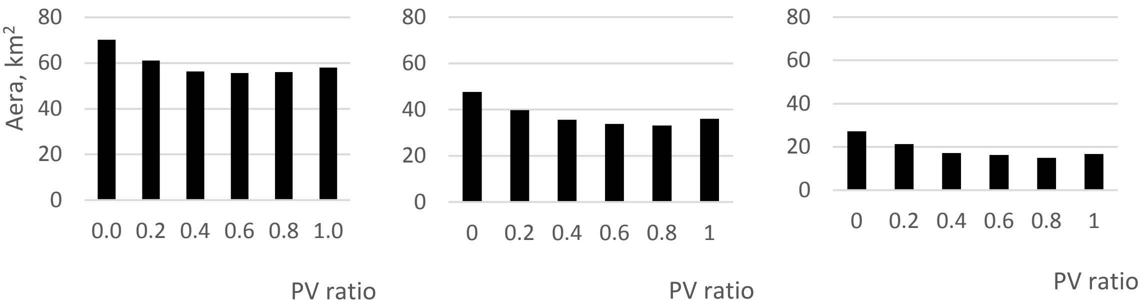

Figure 14 Showing equivalent forest area to offset carbon associated with grid-displaced electricity for scenarios one to three from left to right

5.0 Conclusions

A simple model was developed to estimate energy consumption for a campus development based on specified geometrical and residential parameters. The model was then used to estimate the area required to meet energy demands using renewable and low-carbon technologies. The outputs generated for series of geometries and technology configuration have been used to provide a comparison and estimation of the total area needed for such developments.
It has been shown that denser constructions provide for lower overall electricity and heating demands to a certain point. While the short duration of this study has prevented further exploration of this further studies could examine optimization strategies addressing energy demand versus development height and density.
It has also been noticed that certain mixed compositions of photovoltaics and wind turbines result in less grid-displacement and therefore are more suitable for real-time demand supply. Furthermore, it should be noted that while this model does not consider energy storage opportunities beyond electricity displacement through the national grid, a better understanding would require modelling and simulation of onsite storage technologies, e.g. solid and fluid batteries, flywheels, etc., which could potentially minimize grid-displacement and provide for more practical solution. Nevertheless, the spatial comparison described here provides a glimpse into the potential complications of low-carbon and/or net zero carbon developments of large scale.

6.0 References

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7.0 Acknowledgements

Many thanks to Dr. Abigail Hathway for her support throughout and EPSRC for their financial sponsorship making this study possible.