Assessment of Multi-Domain Energy Systems Modelling Methods

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International Science Index, Energy and Power Engineering Vol:11, No:7, 2017 waset.org/Publication/10007516

Abstract**—**Emissions are a consequence of electricity generation. A major option for low carbon generation, local energy systems featuring Combined Heat and Power with solar PV (CHPV) has significant potential to increase energy performance, increase resilience, and offer greater control of local energy prices while complementing the UK's emissions standards and targets. Recent advances in dynamic modelling and simulation of buildings and clusters of buildings using the IDEAS framework have successfully validated a novel multi-vector (simultaneous control of both heat and electricity) approach to integrating the wide range of primary and secondary plant typical of local energy systems designs including CHP, solar PV, gas boilers, absorption chillers and thermal energy storage, and associated electrical and hot water networks, all operating under a single unified control strategy. Results from this work indicate through simulation that integrated control of thermal storage can have a pivotal role in optimizing system performance well beyond the present expectations. Environmental impact analysis and reporting of all energy systems including CHPV LES presently employ a static annual average carbon emissions intensity for grid supplied electricity. This paper focuses on establishing and validating CHPV environmental performance against conventional emissions values and assessment benchmarks to analyze emissions performance without and with an active thermal store in a notional group of non-domestic buildings. Results of this analysis are presented and discussed in context of performance validation and quantifying the reduced environmental impact of CHPV systems with active energy storage in comparison with conventional LES designs.

Keywords**—**CHPV, thermal storage, control, dynamic simulation.

I. Introduction

ENERGY demand for heat accounts for almost half of all UK energy demand and a third of emissions [1]. The majority of these emissions are space heating and hot water from non-industrial buildings. Strategic heat and electrical energy policies encourage local renewable and other low carbon generation and complement other incentives to reduce demand through energy efficiency. The UK carbon emissions policy for buildings adheres to European Performance of Buildings Directive (EPBD) Standards through mandated energy performance certification [2]. Compliance with UK Building Regulations and EPBD is achieved using quasi-steady state benchmark energy assessment methods; SAP and SBEM [3], [4]. Reporting on carbon equivalent emissions is published annually using CO_2e values derived from the previous year. These values are used in conjunction with metered energy demand to calculate emissions for certification and claiming financial incentives such as Renewables Obligation (RO), Renewable Heat Incentive (RHI), Feed-in Tariffs, and CRC Energy Efficiency Scheme, and CHPQA. There is therefore a strong incentive to accurately predict energy performance and consequent emissions from buildings.

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Dynamic simulation software is valuable to industry in providing a mechanism to rapidly simulate a building or zone to determine and assess its thermal and electrical responses to demands and disturbances [5]. The Inverse Dynamics based Energy Assessment and Simulation (IDEAS) framework is a dynamic modelling and numerical calculation environment developed using Robust Inverse Dynamics Estimation (RIDE) and small perturbation theory to accurately simulate energy utilization and control of complex energy flows in buildings served by one or more low or zero carbon energy sources such as CHP and photovoltaics [6], [7]. The framework has previously been applied to domestic dwellings and calibrated with reference empirical data derived from UK's Standard Assessment Procedure (SAP) for domestic buildings [8].

More recent developments used this framework to develop a new type of local energy system design – Combined Heat and Photovoltaics (CHPV) [9]-[11]. The IDEAS framework is used in this paper to host a complex multi-domain CHPV system with thermal store and establish thermal and electrical energy required to track a desired zonal setpoint temperature at a 1 minute sampling rate. The method uses an optimum start algorithm to implement a near ideal heating system control as a reference performance metric.

II. CHPV System Topology

For this paper, a multi-vector (heat and electricity) local energy system is defined as comprising a non-domestic zone supplied with heat via a heat network from an energy center featuring CHP, gas boiler back-up, and a central hot water store. Appliance density and electricity consumption values appropriate to a nominal real office building were used. Mechanical ventilation with heat recovery technology is represented and also results in additional electrical load when active.

Building cooling is implemented using electrically driven mechanical ventilation with heat recovery technology. Each zone therefore features a full set of controlled space heating, DHW, MVHR, and cooling energy services. A grid-connected

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roof-mounted solar PV array is assumed. Graphically, this energy supply and demand topology is illustrated in Fig. 1. The zone construction is described by parameters indicative of pre-1990 construction standards and energy performance. Building level plant and configuration parameters are summarized in Appendix.

III. Methodology

In this model, heat transfer across a defined building boundary is governed by simultaneous non-linear nodal resolution of four defined building temperature nodes and two system temperature nodes.

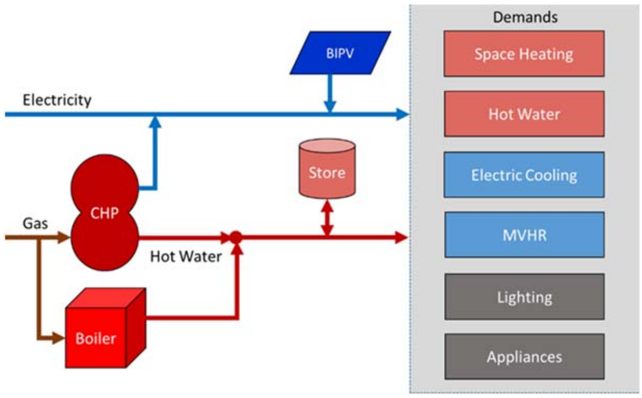

Fig. 1 CHPV local energy system topology

External and internal structural temperature nodes capture dynamics of heat transfer through exterior walls, an internal structural mass temperature node represents immovable structure mass such as load bearing beams and joists, a thermostatically controlled zone temperature node represents both air volume and furniture within a building envelope in a single node, a hot water network temperature node, and a thermal store temperature node. A detailed examination of this thermal resistance approach is given in [8] and results in describing differential equations derived from fundamental building physics. State space representation of these equations then allows implementation and analysis in numerical simulation software such as MATLAB/Simulink. The building model assumes uniformly distributed air volume and zone temperature with fabric u-values assumed in steady state. This bandwidth modelling approach simplifies mathematical representation while retaining detail sufficient for energy assessment and control.

The describing linear differential equations for each modelled building temperature zone are given by (1)-(4):

$$\frac{dT_{zone}(t)}{dt} = \frac{1}{m_{zone}C_{zone}}\Big(U_wA_w + U_fA_f + U_rA_r + U_dA_d + \dot{m}_vC_a + \frac{4h_ik_wA_s}{4k_w+h_id_w} + U_{im}A_{im}\Big)T_{zone}(t) + \frac{4h_ik_wA_s}{m_{zone}C_{zone}(4k_w+h_id_w)+h_id_w}\overline{T_{si}}(t) + \frac{U_{im}A_{im}}{m_{zone}C_{zone}}T_{im}(t) + \frac{1}{m_{zone}C_{zone}}\dot{Q}z_{zone}(t) + \frac{1}{m_{free}C_{free}}\phi_{free}(t) + \frac{1}{m_{zone}C_{zone}}\big(U_wA_w + U_fA_f + U_rA_r + U_dA_d + \dot{m}_vC_a\big)T_o(t) \quad (1)$$

$$\frac{d\overline{T_{si}}(t)}{dt} = \frac{4h_ik_wA_s}{m_{si}C_s(4k_w+h_id_w)}\overline{T_{si}}(t) + \frac{2k_wA_s}{m_{si}C_sd_w}\overline{T_{se}}(t) \quad (2)$$

$$\frac{d\overline{T_{se}}(t)}{dt} = \frac{2k_wA_s}{m_{se}C_sd_w}\overline{T_{si}}(t) - \frac{k_wA_s(8k_w+6h_ed_w)}{m_{se}C_sd_w(4k_w+h_ed_w)}\overline{T_{se}}(t) \quad (3)$$

$$\frac{dT_{im}(t)}{dt} = \frac{U_{im}A_{im}}{m_{im}C_{im}}T_{zone}(t) - \frac{U_{im}A_{im}}{m_{im}C_{im}}T_{im}(t) \quad (4)$$

A hot water network temperature node and thermal store node are described by (5), (6):

$$\frac{d\overline{T_w}(t)}{dt} = \frac{\dot{Q}_{chp}(t)(1-U_{st}(t))}{m_wC_w} + \frac{\dot{m}_wC_w}{m_wC_w}\big(T_{st}(t) - T_w(t)\big)U_{st}(t) - \frac{U_pA_p(T_w(t)-T_{ground}(t))}{m_wC_w} - \frac{(\dot{Q}_{dump}(t)-\dot{Q}_{boiler}(t))}{m_wC_w} \quad (5)$$

$$\frac{d\overline{T_{st}}(t)}{dt} = \frac{\dot{Q}_{chp}(t)U_{st}(t)}{m_{st}C_w} - \frac{\dot{m}_wC_w}{m_{st}C_w}\big(\overline{T_{st}}(t) - \overline{T_w}(t)\big)U_{st}(t) - \frac{U_sA_s(T_{st}(t)-T_{extstore}(t))}{m_{st}C_w} \quad (6)$$

The heat generated from the CHP engine is given by:

$$\dot{Q}_{chp} = K_{QCHP}\,U_{CHP}(t) \quad (7)$$

A simplified resistive electrical model represents real power flows within and across the boundary of the system thus describing primary nodes in a private or local electricity network as follows:

$$P_{GRID}(t) = P_{Load}(t) - P_{GCHP}(t) - P_{GPV}(t) \quad (8)$$

where the total electricity demand $P_{Load}(t)$ is given by:

$$P_{Load}(t) = \textstyle\sum_1^n P_{ZoneLoad.n}(t) \quad (9)$$

where n is the number of building zones.

Power generated by the CHP engine is given by:

$$P_{GCHP} = K_{PCHP}\,U_{CHP}(t) \quad (10)$$

Engine dynamics are approximated by a linear time-invariant first order differential equation to represent its reaction time with a time constant τ_{CHP} to a change in control input $U_{Gas}(t)$ such that:

$$\tau_{CHP}\,\dot{U}_{CHP}(t) = U_{Gas}(t) - U_{CHP}(t) \quad (11)$$

The coupled set of differential equations (1)-(11) together with design input signal are solved in state space as vector functions of time as given by (12), (13):

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{Ax}(t) + \boldsymbol{Bu}(t) + \boldsymbol{Ed}(t) \quad (12)$$

$$\boldsymbol{y}(t) = \boldsymbol{Cx}(t) + \boldsymbol{Du}(t) + \boldsymbol{Fd}(t) \quad (13)$$

Assuming a high gain thermostatic control can isolate temperature control of each zone, the resulting state vector for heat and power networks simplifies to (14):

$$\boldsymbol{x}(t) = [\overline{T_w}(t)\ \overline{T_{st}}(t)\ U_{CHP}(t)]^T \tag{14}$$

The control input vector *u(t)* is defined as

$$u(t) = [U_{st}(t)\ \ U_{Gas}(t)]^T \tag{15}$$

Disturbance vector d(t) is defined as:

$$d(t) = \left[T_{ground}(t)\ \dot{Q}_{dump}(t)\ \dot{Q}_{boiler}(t)\ T_{extstore}(t)\ \ P_{GPV}(t)\ P_{Load}(t)\right]^T \tag{16}$$

The output vector y(t), i.e. the system outputs/feedback measurements to be controlled in the CHP system is defined as:

$$y(t) = [\ \overline{T_w}(t)\quad P_{GRID}(t)\ ]^T \tag{17}$$

By using linearised representations of state equations, the resulting state space A, B, C, D, E, and F matrices shown in (12) and (13) using vectors (14)-(17) are derived as:

$$A = \begin{bmatrix} \frac{-\dot{m}_w c_w\, Uo - U_p A_p}{\tau_w} & \frac{\dot{m}_w c_w\, Uo}{\tau_w} & \frac{K_{QCHP}(1 - Uo)}{\tau_w} \\ \frac{\dot{m}_w c_w\, Uo}{\tau_{st}} & \frac{-\dot{m}_w c_w\, Uo - U_s A_s}{\tau_{st}} & \frac{K_{QCHP}\, Uo}{\tau_{st}} \\ 0 & 0 & \frac{-1}{\tau_{CHP}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{-\dot{Q}_{CHPO} + \dot{m}_w c_w \Delta TO}{\tau_w} & 0 \\ \frac{\dot{Q}_{CHPO} - \dot{m}_w c_w \Delta TO}{\tau_{st}} & 0 \\ 0 & \frac{1}{\tau_E} \end{bmatrix}$$

$$E = \begin{bmatrix} U_p A_p/\tau_w & -1/\tau_w & 1/\tau_w & 0 & 0 & 0 \\ 0 & 0 & 0 & U_s A_s/\tau_{st} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -K_{PCHP} \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and

$$F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

where

$$\tau_{st} = m_{st} c_w \quad and\ \tau_w = m_w c_w \tag{18}$$

IV. System Control

The CHPV control system is required to simultaneously track both a desired grid power transferred to or from the system and a desired system temperature set via thermostat. In this case, these were set to zero electricity transfer and 85 °C respectively during occupancy. These set points can be described mathematically for controller implementation in a set point vector v(t) which is given by:

$$v(t) = [358.15\quad 0]^T \tag{19}$$

The general schematic form of the RIDE controller design method is shown in Fig. 2.

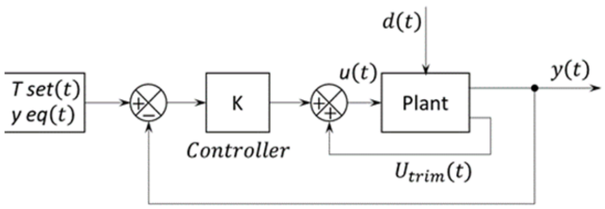

Fig. 2 RIDE control structure

The RIDE controller design methodology solves the inverse dynamic problem of a multi-input multi-output control system. Given a desired set point vector *v(t)* to track, the control input vector *u(t)* must equate to the inverse dynamics law to give the set of decoupled linear first order responses. This control law is given by:

$$u_c(t) = g(\boldsymbol{CB})^{-1}\big(v(t) - (t)\big) \tag{20}$$

$$u_{trim}(t) = (\boldsymbol{CB})^{-1}\big(\boldsymbol{CA}x(t) + \boldsymbol{E}d(t)\big) \tag{21}$$

Such that:

$$u(t) = u_c(t) + u_{trim}(t) \tag{22}$$

The response of the closed-loop system is therefore two first order closed-loop system responses given by (23):

$$y(t) = (1 - e^{-gt})v(t) \tag{23}$$

Under these conditions and as t→∞ then y(t)→v(t). The resulting response tracks with zero steady state error, thus the RIDE method allows implementation of an idealized control and hence generates a benchmark against which realistic controls can be designed and tested. In many instances as has proven in this case, a high enough gain value g can be achieved such that $u_c(t) \gg u_{trim}(t)$, and in such case then, the control law for inverse dynamics can be approximated by equation (20). Invertability, stability, and reachability analysis is outside the scope of this paper and is fully described in [9].

V. Simulation Results

Fig. 3 shows baseline electrical demand for the modelled building at 1 minute steps for 1 year. The repeating pattern of 725 kW demand during weekday occupancy, 300 kW at weekends with 125 kW night time setback power demand is apparent with additional demand during summer months in electrical energy for cooling.

Simulated annual electrical energy demand for this building is 396,000 kWh/yr, or 137kWh/m^2/yr.

Fig. 4 shows baseline resultant zone thermal performance against thermostat setpoints and outdoor temperature. A variation of -3 degrees during winter and +3 degrees during summer results in a maintained profile variation of 6 degrees for the year.

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Baseline carbon efficiency for this configuration is equal to 1 as expected and shown in Fig. 5.

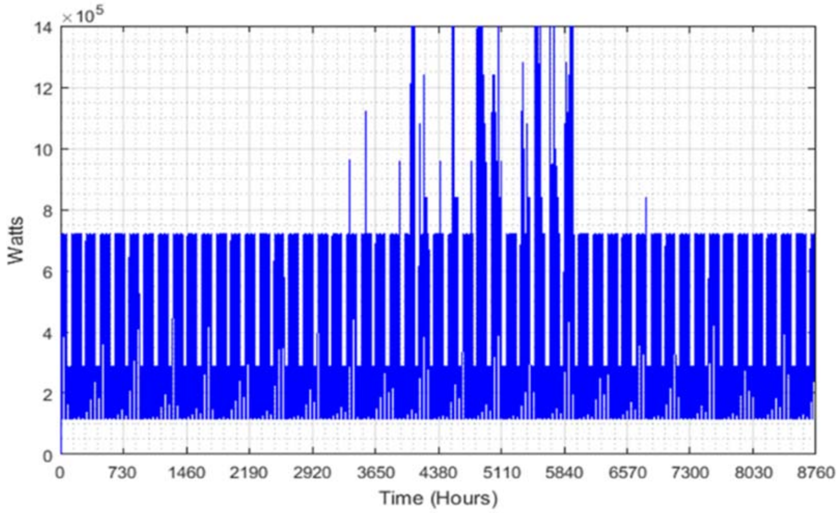

Fig. 3 Simulated baseline electricity demand

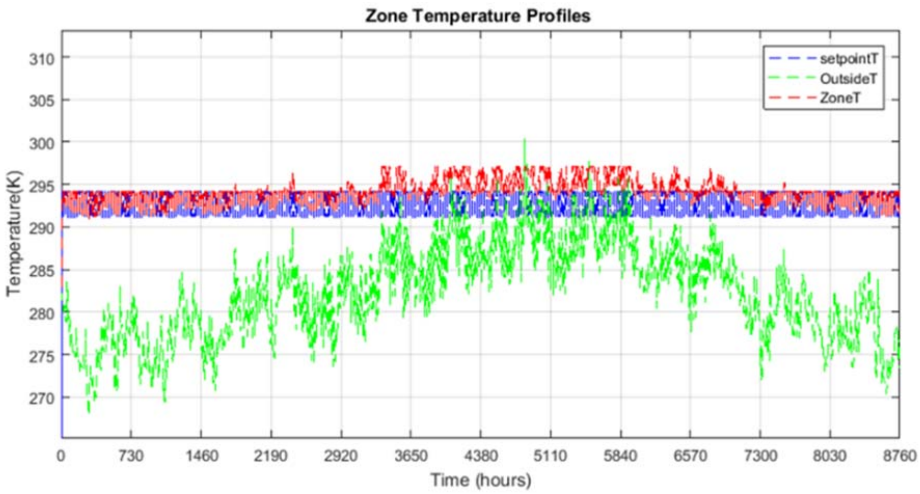

Fig. 4 Simulated baseline thermal performance

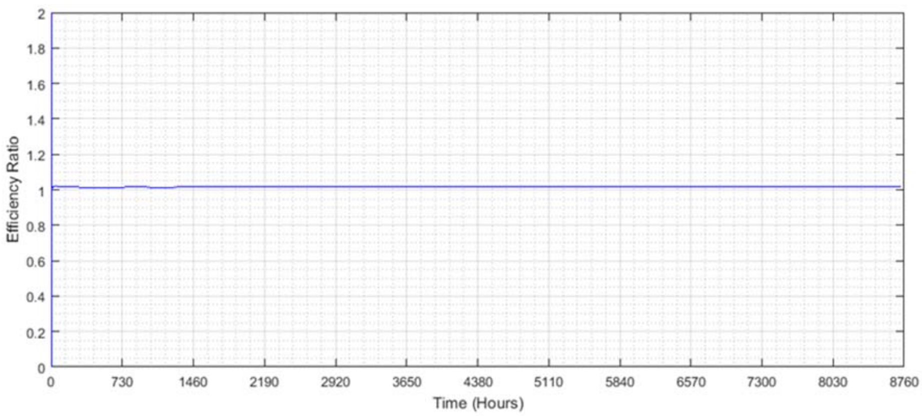

Fig. 5 Baseline carbon efficiency ratio

The model was reconfigured to include CHP engine, solar PV array, and thermal store. Results are as presented below. As Fig. 6 shows, CHPV configuration results in almost identical thermal performance.

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Carbon emissions performance of the CHPV configuration relative to conventional grid and gas boiler is given in Fig. 7.

A comparative modelling summary of relevant parameters is given in Table I.

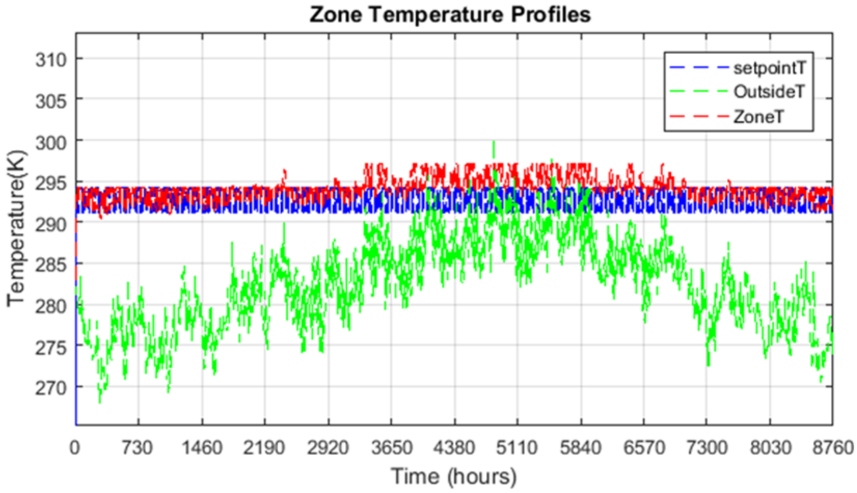

Fig. 6 CHPV thermal performance

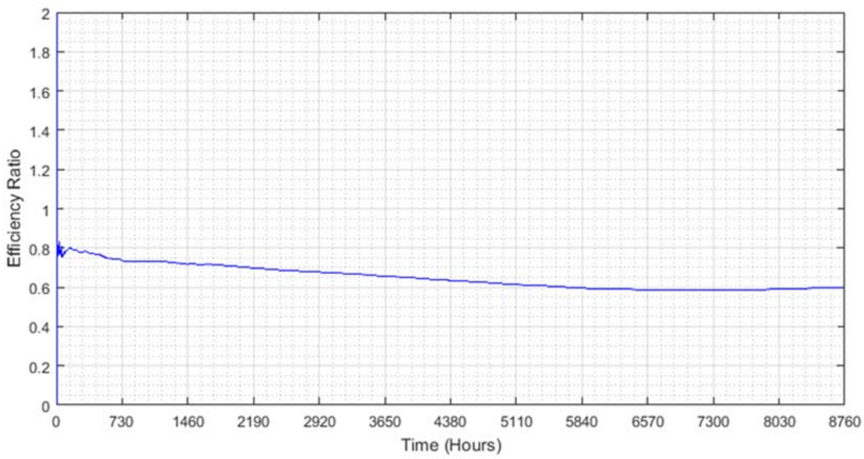

Fig. 7 Relative carbon emissions of CHPV to 2015 baseline

TABLE I
COMPARATIVE MODELLING SUMMARY

LES Plant	Baseline	CHPV Configuration
Grid Elec	X	X
Gas Boiler	X	X
PV		X
CHP		X
Thermal Store		X
Gas Boiler Fraction	100%	32.8%
Gas Import (MWh)	5102	9317
Emissions tCO_2e	3000	1720
System Eff.	86%	75%
Grid Relative Carbon	1.00	0.59

VI. Discussion

This paper has extended knowledge of CHPV performance to its emissions reduction potential by developing a routine to compare simulation results from a conventional configuration to that of a CHPV with thermal store configuration. Addition and integrated control of CHP, solar PV and thermal store is seen to result in an emissions reduction potential of over 40% against baseline grid electric and gas boiler scenario by shifting dependency on external energy supply from relatively carbon intensive electricity to lower carbon gas. Simulated gas usage was split with 2/3rds being consumed by the CHP engine.

The assumed continuing reduction in grid electricity carbon intensity will, without further CHPV system optimisation or change in configuration, reduce the emissions reduction potential of present CHPV design. However, the cost of such low carbon electricity will likely have the effect of bolstering the case for continuing use of relatively cheap gas for both heat and power in buildings well beyond 2030. This scenario and the associated analysis of dynamic carbon values for fuels are the basis for future work and publication.

VII. Conclusions

This paper has presented a method of comparing emissions impact of dynamic models of non-domestic buildings and their servicing systems. The IDEAS method adopted was extended to incorporate dynamics of non-domestic buildings with photovoltaics served by building integrated CHP, heat network and local thermal store. In this paper, an idealised high gain proportional control was assumed in conjunction with an optimum start algorithm to generate ideally controlled system energy baselines. Results show CHPV configuration with energy storage can result in a 40% improvement over baseline emissions from a conventional system consisting of grid electricity and gas boilers using reference 2015 CO_2e values for natural gas and grid electricity supplies. Dynamic simulation of buildings and their servicing systems provides valuable design and performance tools to the industry. Accurate representation of models against a verified and trusted baseline is critical in this process. The IDEAS based framework used in this paper performed with consistent scalable results.

Appendix-Baseline Configuration

The baseline configuration is a notional pre-1990's non-residential building.

TABLE II
Baseline Configuration Parameters

Primary Activity	Notional non-domestic Building
Building Gross Internal Area (GIA)	28,800 m^2
CHP Engine	200 kWe rated
Solar PV	12,000m^2 Roof Mounted
Electric Cooling	680 kW DX VRF
Ventilation	Mechanical with 70% heat recovery

Service and plant efficiencies are also known for this design, given in Table III below.

TABLE III
Service & Plant Efficiencies

	Efficiency	EER	SEER
Chillers		3.5	5.5
Gas Boilers	91%		
DX VRF		3.5	3.5
Hot Water	95%		
CHP	42% / 42%		
PV	130 kWh/m^2/yr		
Pumps	Variable speed		
AHU Fan Power	1.6 sfp		
FCU Fan Power	0.5 sfp		
Extract Fan Power	0.4 sfp		

Additional known design information includes fabric u-values and assumed control regimes for heating, ventilation, cooling and lighting as given in Tables IV and V.

TABLE IV
Test Case U-Values

	Floor	Roof	Wall	Glazing	Doors
U-value	1.5	1.5	2	1.7	1.7

TABLE V
Service Controls

	Control Regime
Heating	Auto
Ventilation (MVHR)	Continuous
Electric Cooling	Auto during occupancy
Domestic Hot Water	Auto during occupancy
Lighting	Auto on / off

Nomenclature

T_{zone} Zone Temperature (K)
$\overline{T_{si}}$ Mean internal temperature of structure (K)
$\overline{T_{se}}$ Mean external temperature of structure (K)
T_{im} Mean internal mass temperature (K)
T_o Mean external dry bulb temperature (K)
T_w Mean water network temperature (K)
T_{st} Mean store temperature (K)
m_{zone} Air and furniture mass (kg)
m_{si} Mass of internal structure (kg)
m_{se} Mass of external structure (kg)
m_{im} Mass of internal furniture (kg)
m_s Mass of store (kg)
$\dot{m}_w$ Mass flowrate of water in network (kg)
$\dot{m}_v$ Air infiltration rate (kg/s)
U_w U value of windows $(W/(m^2K))$
U_f U value of floor $(W/(m^2K))$
U_r U value of roof $(W/(m^2K))$
U_d U value of doors $(W/(m^2K))$
U_{im} U value of internal mass $(W/(m^2K))$
U_{st} U value of store $(W/(m^2K))$
A_w Area of windows (m^2)
A_f Area of floor (m^2)
A_r Area of roof (m^2)
A_d Area of doors (m^2)
A_s Area of wall structure (m^2)
A_{im} Area of internal mass (m^2)
h_i Heat transfer coefficient $(W/(m^2K))$
d_w Structure thickness (m)
C_{zone} Thermal capacity of defined zone $(W/(m^2K))$
ϕ_h Total heat transfer (W)
ϕ_{free} Free heat gains (W)
C_a Thermal capacity of air $(W/(m^2K))$
C_s Thermal capacity of store $(W/(m^2K))$
C_{im} Thermal capacity of internal mass $(W/(m^2K))$
C_w Thermal capacity of water $(W/(m^2K))$
$\dot{Q}_{chp}$ Rate of thermal energy supply (W)
$\dot{Q}_{loss}$ Rate of thermal energy loss (W)

Acknowledgments

This research and paper has been funded by EPSRC through funding of the CHPV Project (REF: 101998) and Heat-STRESS Project (REF: EP/N02155X/1). The authors gratefully acknowledge funding for this work.

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