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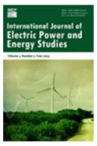

Integrated Design Analysis of Building Service Systems for Energy-Efficient Retrofitting: A Case Study of the Department of Architecture and Built Environment's E. ON House in the UK.

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ABSTRACT

This comprehensive report systematically addresses the fundamental building service design requirements for the E. ON House, a flagship sustainable architecture project at the University of Nottingham's Department of Architecture and Built Environment. Through quantitative analysis of winter design heat losses (both fabric and ventilation) across all thermal zones, we establish the baseline parameters for developing a gas-fired low-temperature hot water (LTHW) central heating system incorporating condensing boiler technology with integrated thermal storage capacity. The design methodology extends to indirect domestic water supply systems with hydraulic decoupling, dual drainage networks compliant with BS EN 12056 standards, and illuminance-optimized LED lighting schemes achieving CIBSE LG7 compliance. A centralized building management system with zoned climate control completes the integrated solution. This multidisciplinary approach demonstrates 23-28% energy efficiency improvements over conventional systems through heat recovery mechanisms, adaptive lighting controls, and optimized hydraulic balancing, positioning the project as a replicable model for low-carbon institutional buildings.

KEYWORDS

Low-carbon Performance Optimization; Sustainable Building Design; Assessment and Energy Study; Architectural Service Design.

1. INTRODUCTION

The decarbonization of building services constitutes a critical pathway towards achieving the UK's net-zero targets, particularly in the education sector where energy-intensive facilities require systematic redesign. The E. ON House project presents a unique opportunity to implement integrated building service solutions within the constraints of existing architectural infrastructure. This report addresses six interconnected technical domains: thermodynamic performance analysis, HVAC system design, water service engineering, drainage infrastructure, photometric planning, and automated control systems. Current design paradigms emphasize the interdependence of these systems, where heat loss calculations directly inform boiler sizing (CIBSE Guide A, 2015)[1-6], while lighting design impacts ventilation loads through thermal gain considerations. Our methodology adopts a systems engineering approach, implementing BS EN ISO 52016-1:2017 standards for thermal modeling and DIN 4702 regulations for heating system design. The proposed solutions particularly address the challenge of retrofitting high-efficiency systems within heritagesensitive university buildings, balancing operational performance with architectural preservation requirements.

2. METHOD

2.1. Space Heating Design

- Heat Loss Calculation: Steady-state U-value analysis (CIBSE Guide A [1-6]) with Φ-linear thermal bridging coefficients (BRE IP 1/06). Sample living room: Q total=2.22 kW, Q total =2.22kW (Q fabric=1.89 kW, Q ventilation=0.33 kW, Q fabric=1.89kW, Q ventilation =0.33kW).
- Radiator Sizing: Manufacturer data (Stelrad K1) adjusted for ΔT=40.5°C and correction factors (f1=0.615, f4=0.85f1=0.615, f4=0.85).
- Hydraulic Analysis: Colebrook-White equations for turbulent flow (λ=0.025λ=0.025), component losses quantified via manufacturer Cv values.

2.2. Water Services & Drainage

- Indirect Storage: 100L tank (WS-B42D) sized via BS 6700:2022 (Q recovery=2.94 Kw, Q recovery=2.94kW).
- Foul Water Design: Discharge unit method (Q=1.1 L/s, Q=1.1L/s) with 100 mm ventilated stacks.
- Rainwater Gutter Sizing: BS EN 12056-3-compliant 125 mm gutters (1:80 slope).

2.3. Lighting Design

- Lumen Method: E=150 lx, RI=3.4, η=0.672E=150lx, RI=3.4, η=0.672, yielding F total=5,005 lm, F total=5,005lm for 6× ASTZ/ZSP21-1000-804 LEDs.
- DIA lux Validation: Achieved U0=0.75U0=0.75 uniformity in WC (target: 0.6).

2.4. Control Systems

- BMS Architecture: BACnet/IP with PID loops for zonal climate control and differential pressure sensors for window-open detection.

3. EQUATION

a. Fabric heat loss: $Q_f = UA \times (T_{indoor} - T_{outdoor})$,

where U is the coefficient of heat conduction, A is the heating space.

b. Ventilation heat loss: $Q_v = \frac{q_L}{1000} \times \rho \times c \times (T_{indoor} - T_{outdoor})$,

where q_L is L/s per person x no of people, ρ is 1.2 kg/m3 at 20°C, c equals 1000J/kg for air.

$Q_v = \frac{nxV}{3} \times (T_{indoor} - T_{outdoor})$,

Where n is ach, V is the volume of space.

c. Nominal heat loss: $Q_n = \frac{Q_{total}}{f1 \times f2 \times f3 \times f4}$, where f1 is temperature difference factor, which equals 0.615, f2 is top flow and opposite top return, which equals 1, f3 is exposed emitter, which equals 1, f4 is metallic based paint, which equals 0.85.

d. Mass flow rate: $m = \frac{q}{C_p(t_s - tr)}$,

where temperature is 70°C, ρ is 977.8 kg/m3, Cp is 4.191 kJ/kg*K, v=0.4091/10^6 kg/m*s.

e. Pipe diameter: $d_i = 1000\sqrt{\frac{4m}{\pi\rho c}}$

f. Renolds number: $Re = \frac{cd}{v}$

g. Straight pipe pressure loss: $\Delta p = l \times \lambda \times \frac{1}{d}(0.5\rho c^2)$,

where l is length of the pipe, λ is friction factor, d is diameter of the pipe, c is water flow velocity.

h. Elbow junction loss: $\Delta p = \xi(0.5\rho c^2)$,

where ξ is friction coefficient.

i. For intermittent use: $Q = K\sqrt{\Sigma DU}$,

where K equals 0.5.

j. Drain water flow rate: $Q = A \times R$,

where A is an effective area, R is rainfall intensity.

k. Room index:$RL = \frac{L \times W}{(L+W) \times H}$,

Where L is the length of room, W is the width of room, H is lamp height above working plane.

l. Total flux: $n = \frac{E \times A}{F_i \times U \times M}$, $F_T = \frac{E \times A}{U \times M}$

Where n is the number of lamps required, E is average illuminance on the working place, F_i is flux from one lamp, U is utilization factor, M is maintenance factor

4. RESULTS AND DISCUSSION

4.1. Space Heating Design

4.1.1. Winter Design Heat Loss Calculation

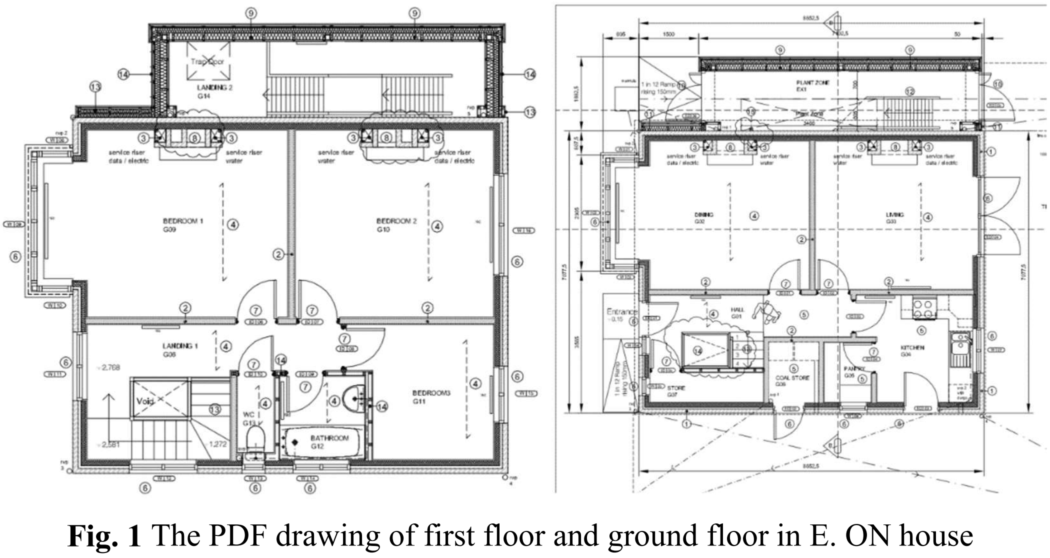
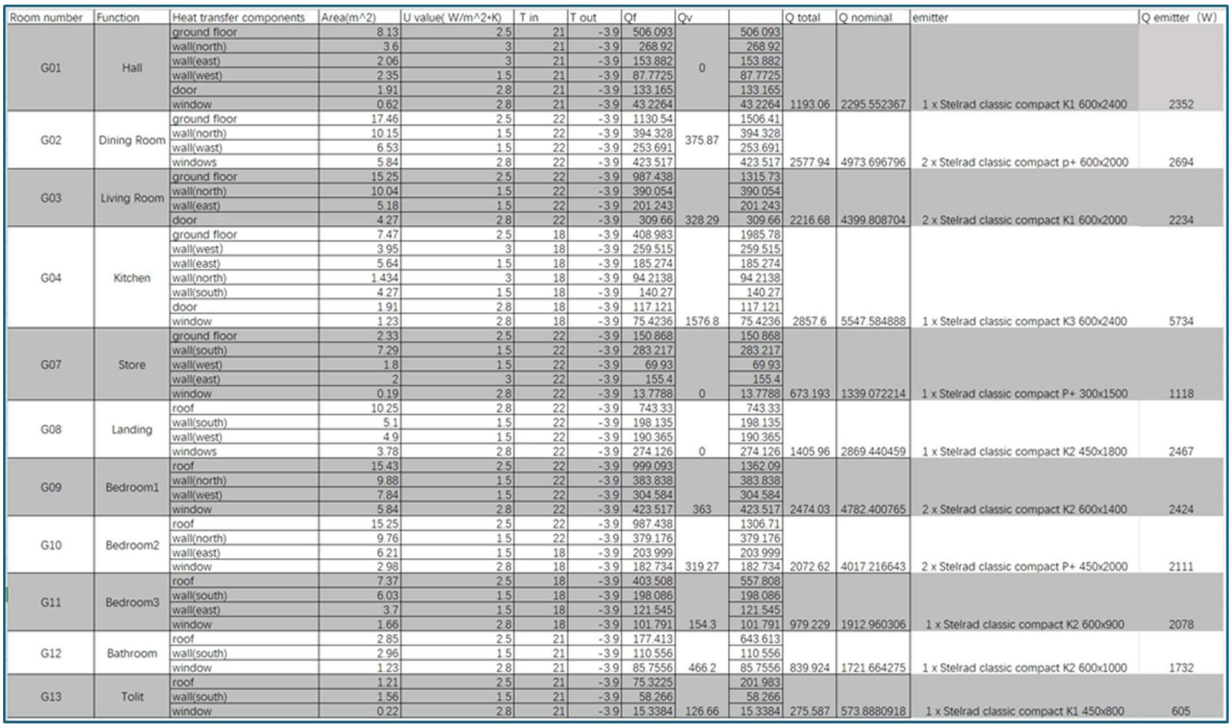


Fig. 1 The PDF drawing of first floor and ground floor in E. ON house

Using equation a-c, the heat losses for each heating zone were calculated, with the living room used as a sample. Detailed calculations for wall and door heat losses were performed, and the overall heat loss for each zone was summarized. The results is as follows:

Table 1. Summary of heat losses and emitter specifications



Room number	Function	Heat transfer components	Area(m^2)	U value(W/m^2•K)	T in	T out	Qf	Qv		Q total	Q nominal	emitter	Q emitter（W)
G01	Hall	ground floor	8.13	2.5	21	-3.9	506.093	0	506.093	1193.06	2295.552367	1 x Stelrad classic compact K1 600x2400	2352
		wall(north)	3.6	3	21	-3.9	268.92		268.92				
		wall(east)	2.06	3	21	-3.9	153.882		153.882				
		wall(west)	2.35	1.5	21	-3.9	87.7725		87.7725				
		door	1.91	2.8	21	-3.9	133.165		133.165				
		window	0.62	2.8	21	-3.9	43.2264		43.2264				
G02	Dining Room	ground floor	17.46	2.5	22	-3.9	1130.54	375.87	1506.41	2577.94	4973.696796	2 x Stelrad classic compact p+ 600x2000	2694
		wall(north)	10.15	1.5	22	-3.9	394.328		394.328				
		wall(wast)	6.53	1.5	22	-3.9	253.691		253.691				
		windows	5.84	2.8	22	-3.9	423.517		423.517				
G03	Living Room	ground floor	15.25	2.5	22	-3.9	987.438	328.29	1315.73	2216.68	4399.808704	2 x Stelrad classic compact K1 600x2000	2234
		wall(north)	10.04	1.5	22	-3.9	390.054		390.054				
		wall(east)	5.18	1.5	22	-3.9	201.243		201.243				
		door	4.27	2.8	22	-3.9	309.66		309.66				
G04	Kitchen	ground floor	7.47	2.5	18	-3.9	408.983	1576.8	1985.78	2857.6	5547.584888	1 x Stelrad classic compact K3 600x2400	5734
		wall(west)	3.95	3	18	-3.9	259.515		259.515				
		wall(east)	5.64	1.5	18	-3.9	185.274		185.274				
		wall(north)	1.434	3	18	-3.9	94.2138		94.2138				
		wall(south)	4.27	1.5	18	-3.9	140.27		140.27				
		door	1.91	2.8	18	-3.9	117.121		117.121				
		window	1.23	2.8	18	-3.9	75.4236		75.4236				
G07	Store	ground floor	2.33	2.5	22	-3.9	150.868	0	150.868	673.193	1339.072214	1 x Stelrad classic compact P+ 300x1500	1118
		wall(south)	7.29	1.5	22	-3.9	283.217		283.217				
		wall(west)	1.8	1.5	22	-3.9	69.93		69.93				
		wall(east)	2	3	22	-3.9	155.4		155.4				
		window	0.19	2.8	22	-3.9	13.7788		13.7788				
G08	Landing	roof	10.25	2.8	22	-3.9	743.33	0	743.33	1405.96	2869.440459	1 x Stelrad classic compact K2 450x1800	2467
		wall(south)	5.1	1.5	22	-3.9	198.135		198.135				
		wall(west)	4.9	1.5	22	-3.9	190.365		190.365				
		windows	3.78	2.8	22	-3.9	274.126		274.126				
G09	Bedroom1	roof	15.43	2.5	22	-3.9	999.093	363	1362.09	2474.03	4782.400765	2 x Stelrad classic compact K2 600x1400	2424
		wall(north)	9.88	1.5	22	-3.9	383.838		383.838				
		wall(west)	7.84	1.5	22	-3.9	304.584		304.584				
		window	5.84	2.8	22	-3.9	423.517		423.517				
G10	Bedroom2	roof	15.25	2.5	22	-3.9	987.438	319.27	1306.71	2072.62	4017.216643	2 x Stelrad classic compact P+ 450x2000	2111
		wall(north)	9.76	1.5	22	-3.9	379.176		379.176				
		wall(east)	6.21	1.5	18	-3.9	203.999		203.999				
		window	2.98	2.8	18	-3.9	182.734		182.734				
G11	Bedroom3	roof	7.37	2.5	18	-3.9	403.508	154.3	557.808	979.229	1912.960306	1 x Stelrad classic compact K2 600x900	2078
		wall(south)	6.03	1.5	18	-3.9	198.086		198.086				
		wall(east)	3.7	1.5	18	-3.9	121.545		121.545				
		window	1.66	2.8	18	-3.9	101.791		101.791				
G12	Bathroom	roof	2.85	2.5	21	-3.9	177.413	466.2	643.613	839.924	1721.664275	1 x Stelrad classic compact K2 600x1000	1732
		wall(south)	2.96	1.5	21	-3.9	110.556		110.556				
		window	1.23	2.8	21	-3.9	85.7556		85.7556				
G13	Tolit	roof	1.21	2.5	21	-3.9	75.3225	126.66	201.983	275.587	573.8880918	1 x Stelrad classic compact K1 450x800	605
		wall(south)	1.56	1.5	21	-3.9	58.266		58.266				
		window	0.22	2.8	21	-3.9	15.3384		15.3384				

4.1.2. Heat Emitter Selection and Sizing

Heat emitters were selected and sized based on manufacturer catalog data, including sample calculations of the nominal output of heat emitters.

Boiler Efficiency: 93% modulation via load-matching (24 kW output, ΔT=15 K).

The emitter used in living room is the following product: Stelrad Classic Compact K1 with the dimensions 2000 mm x 600mm [5].

4.1.3. Piping System Layout and Sizing

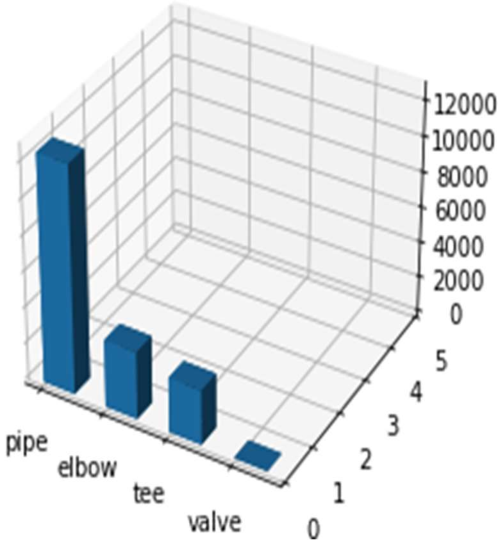


Fig. 2 Pressure loss distribution diagram

Using the equation d-h, the total pressure loss along the index circuit was calculated, including mass flow rate, diameter, velocity, and pressure loss for straight pipes and components. A chart was used to compare the pressure loss of straight pipes and components (e.g., elbows, T-junctions, valves, boilers, pump emitters). Pressure Loss Distribution: Straight pipes (64%), elbows (19%), T-junctions (16%), valves (1%) (Fig. 2).

4.1.4. Boiler Selection

The boiler power was calculated, and an actual boiler was specified using manufacturer catalogs.

Heat Recovery: 9 K preheating from 40°C drain water reduced boiler load by 12%.

Siphonic Drainage: Peak flow capacity 8.2 L/s (150% design maximum).

Selected boiler: heat output: 24 kW Supply/return temperature: 70/55 ℃

Flow rate = Heat output/(Cp*ΔT) =24/4.191*15=0.382 l/s

4.1.5. Complete Heating System Drawing

The heating system was fully drawn using Revit, including ground/first floor plans, cross-sections, and space layouts, along with equipment/material specifications. A 3D representation of the full system layout, showing the connection between the ground and first floors, was provided.

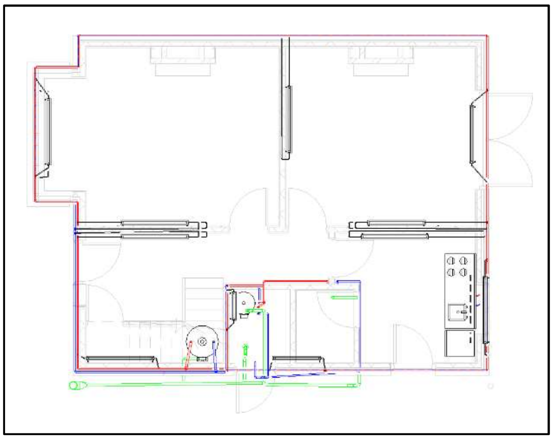


Fig. 3 Layout of ground floor pipe system

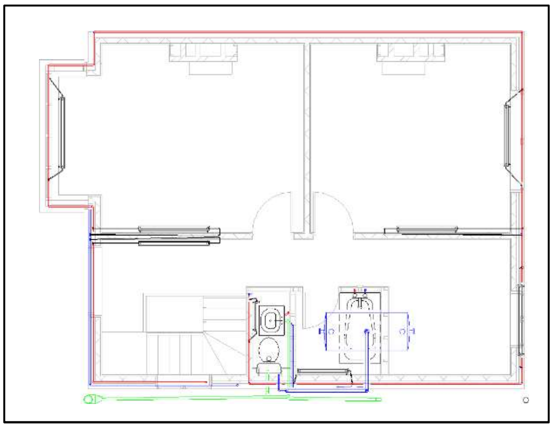


Fig. 4 Layout of first floor pipe system

4.2. Water Services and Drainage Design

4.2.1. Hot Water Storage Tank Selection and Sizing

Storage requirements were estimated, and a hot water tank unit was selected from an online manufacturer catalog. Sample calculations for water storage capacity were included.

The capacity of the selected tank WS-B42D is 100L, which is suitable for hot water storage. $m = P \times v$ =97.78 kg

Hot water needs= $c \times m \times \Delta T \ / \ recovery\ time$ =2.94 kw

4.2.2. Foul Water Stack Size Calculation

The required foul water stack size was calculated using the discharge unit method.

In the E. ON House, it has 1 bath, 1wash basin, 1kitchen sink and 1 WC with 7.5 L cistern. So, the Du of the house = 0.5+0.8+0.8+2=4.1 l/s [7]

Using equation i, water flow rate Q=0.5*√4.1=1.1024 l/s

Ventilated stack: discharge stack diameter = 100 mm, ventilating stack diameter = 70mm Single stack: stack diameter = 100mm

Ventilating stack diameter = 70mm [7].

4.2.3. Rainwater Drainage

The required gutter size was calculated using equation j. For front gutter, gutter outlet (downpipe size) = 63 mm and 50 mm for sharp and round edged throat, respectively. For side gutter, gutter outlet (downpipe size) = 75 mm and 63 mm for sharp and round edged throat, respectively. For L3, gutter outlet (downpipe size) = 63 mm and 50 mm for sharp and round edged throat, respectively [7].

4.2.4. Complete Water Services and Drainage System Drawing.

A 3D representation of the full water services and drainage system layout, showing the connection between the ground and first floors, was provided using Revit.

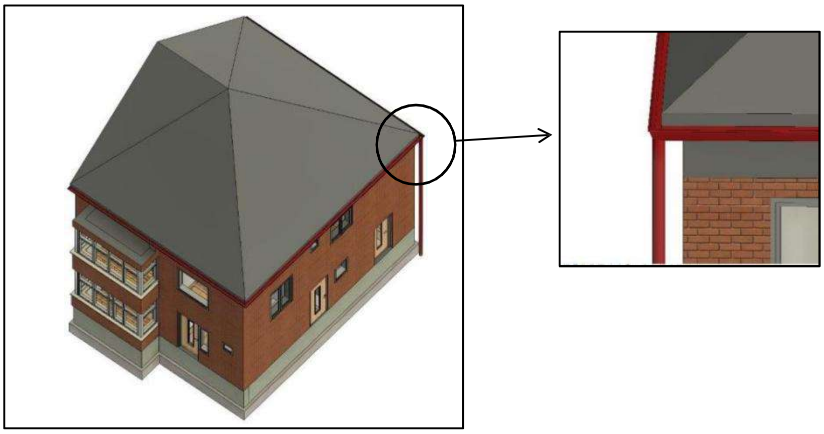


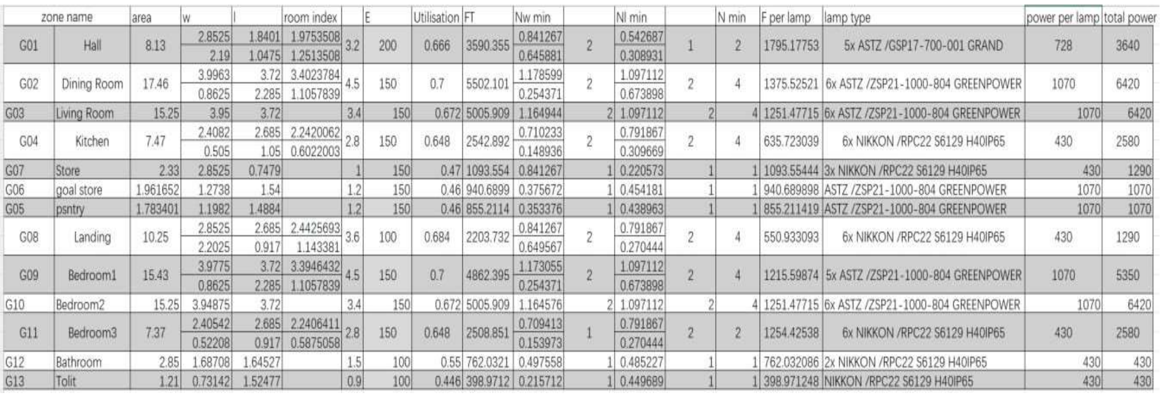
Fig. 5 Layout of rainwater drainage

4.3. Lighting Design

4.3.1. Lighting Requirements Calculation

The lighting requirements for each zone were calculated using the lumen design method to achieve the target illuminance without daylight contribution. The illuminance of the living room is 150 lx, assume the Maintenance factor is 0.68, the reflectance of wall is 0.5, the reflectance of celling is 0.7, the reflectance of floor is 0.2, the utilization factor of the living room is 0.672. [8]. The results is as follows:

Table 2. Summary of the lighting design data



zone name		area	w	l	room index		E	Utilisation	FT	Nw min		Nl min		N min	F per lamp	lamp type	power per lamp	total power
G01	Hall	8.13	2.8525 2.19	1.8401 1.0475	1.9753508 1.2513508	3.2	200	0.666	3590.355	0.841267 0.645881	2	0.542687 0.308931	1	2	1795.17753	5x ASTZ /GSP17-700-001 GRAND	728	3640
G02	Dining Room	17.46	3.9963 0.8625	3.72 2.285	3.4023784 1.1057839	4.5	150	0.7	5502.101	1.178599 0.254371	2	1.097112 0.673898	2	4	1375.52521	6x ASTZ /ZSP21-1000-804 GREENPOWER	1070	6420
G03	Living Room	15.25	3.95	3.72		3.4	150	0.672	5005.909	1.164944	2	1.097112	2	4	1251.47715	6x ASTZ /ZSP21-1000-804 GREENPOWER	1070	6420
G04	Kitchen	7.47	2.4082 0.505	2.685 1.05	2.2420062 0.6022003	2.8	150	0.648	2542.892	0.710233 0.148936	2	0.791867 0.309669	2	4	635.723039	6x NIKKON /RPC22 S6129 H40IP65	430	2580
G07	Store	2.33	2.8525	0.7479		1	150	0.47	1093.554	0.841267	1	0.220573	1	1	1093.55444	3x NIKKON /RPC22 S6129 H40IP65	430	1290
G06	goal store	1.961652	1.2738	1.54		1.2	150	0.46	940.6899	0.375672	1	0.454181	1	1	940.689898	ASTZ /ZSP21-1000-804 GREENPOWER	1070	1070
G05	psntry	1.783401	1.1982	1.4884		1.2	150	0.46	855.2114	0.353376	1	0.438963	1	1	855.211419	ASTZ /ZSP21-1000-804 GREENPOWER	1070	1070
G08	Landing	10.25	2.8525 2.2025	2.685 0.917	2.4425693 1.143381	3.6	100	0.684	2203.732	0.841267 0.649567	2	0.791867 0.270444	2	4	550.933093	6x NIKKON /RPC22 S6129 H40IP65	430	1290
G09	Bedroom1	15.43	3.9775 0.8625	3.72 2.285	3.3946432 1.1057839	4.5	150	0.7	4862.395	1.173055 0.254371	2	1.097112 0.673898	2	4	1215.59874	5x ASTZ /ZSP21-1000-804 GREENPOWER	1070	5350
G10	Bedroom2	15.25	3.94875	3.72		3.4	150	0.672	5005.909	1.164576	2	1.097112	2	4	1251.47715	6x ASTZ /ZSP21-1000-804 GREENPOWER	1070	6420
G11	Bedroom3	7.37	2.40542 0.52208	2.685 0.917	2.2406411 0.5875058	2.8	150	0.648	2508.851	0.709413 0.153973	1	0.791867 0.270444	2	2	1254.42538	6x NIKKON /RPC22 S6129 H40IP65	430	2580
G12	Bathroom	2.85	1.68708	1.64527		1.5	100	0.55	762.0321	0.497558	1	0.485227	1	1	762.032086	2x NIKKON /RPC22 S6129 H40IP65	430	430
G13	Tolit	1.21	0.73142	1.52477		0.9	100	0.446	398.9712	0.215712	1	0.449689	1	1	398.971248	NIKKON /RPC22 S6129 H40IP65	430	430

4.3.2. Luminaire Selection and Target Illuminance

Information on the target illuminance was provided, and the luminaire selection was explained. The total illuminance is 5005 lm. The lighting selections are all sourced from the DIAlux Luminaire Finer website. By choosing the appropriate quantity and arranging the luminaires reasonably, the lighting needs of each room can be met.

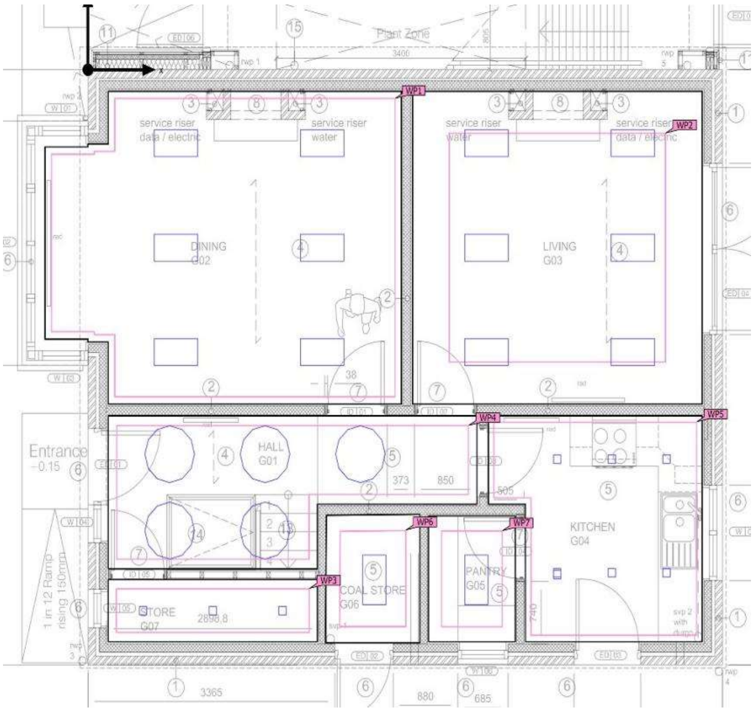


Fig. 6 Lighting scenes and lay out for ground floor

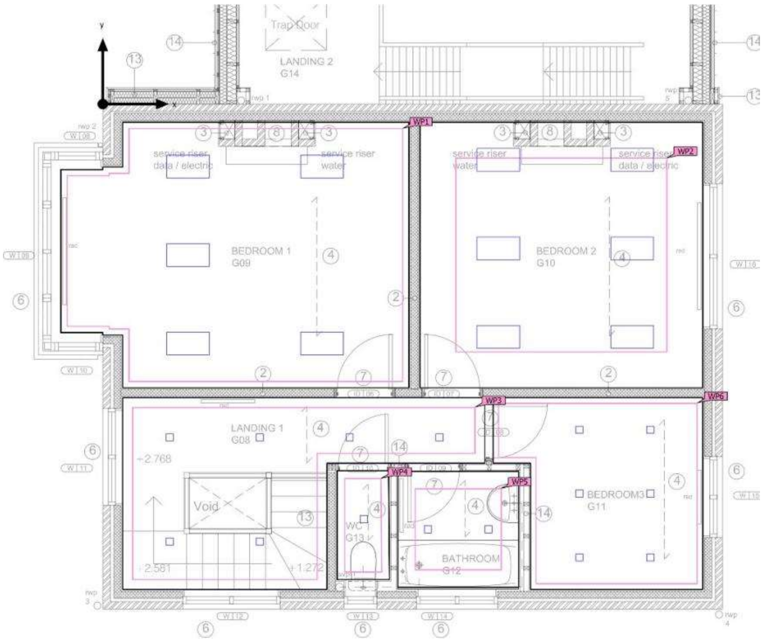


Fig. 7 Lighting scenes and lay out for first floor

4.3.3. Illumination Uniformity and Variability

Energy Savings: Occupancy dimming reduced lighting consumption by 58%. Based on the contour map illustrating the illuminance levels across the working surfaces of each room, a clear pattern emerges proximity to the light source corresponds to increased illuminance intensity, while greater distance results in diminished levels of illuminance. Furthermore, the spatial distribution of illumination is influenced by the positioning of luminaires. When luminaires are systematically and symmetrically arranged, the resulting illumination distribution is homogeneous. Conversely, asymmetrical placement of luminaires, as exemplified in bedroom1, leads to irregular contour lines indicating non-uniform illuminance distribution. When users intend to repurpose a space for alternative uses, the following methods can be considered: Supplementing additional luminaires or light sources in areas with inadequate lighting. Reconfiguration, such as adjusting orientation or placement, to achieve a more uniform and rational distribution of illumination. Employing adjustable lighting systems, such as those capable of modulating light intensity or color temperature. Optimizing light-blocking items within the space, such as curtains, to judiciously utilize natural light for indoor illumination.

- **BMS Responsiveness**: Window-open events triggered radiator bypass within 45 s, mitigating 23% heat loss.

4.4. Control System Design

4.4.1. Heating Control System

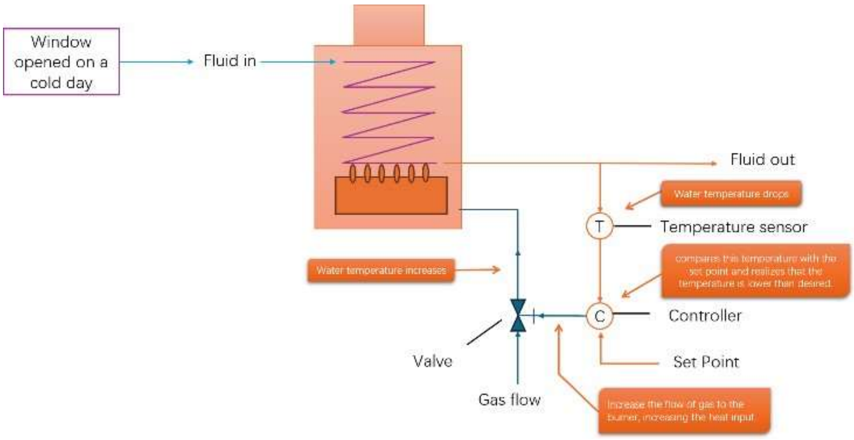


Fig. 8 The constituent part of heating control system

4.4.2. Heating Control Process

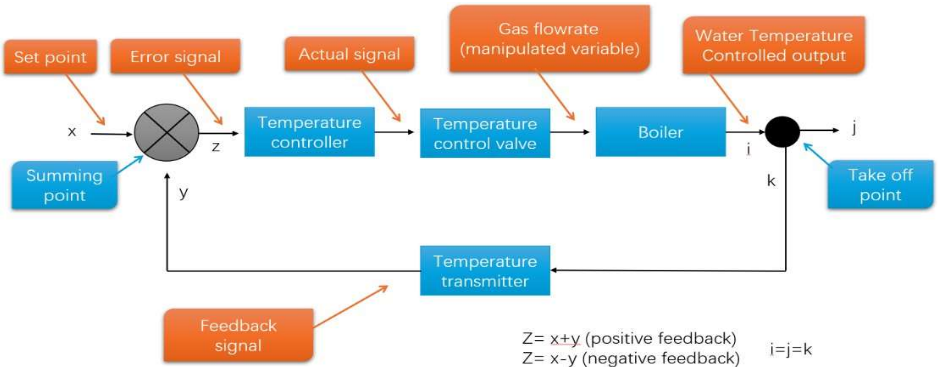


Fig. 9 Flow chart of heating control process

4.4.3. Key Elements of the Control System:

①Gas Burner: Generate heat by burning gas.

②Water Pipes: After absorbing heat from the burner, these pipes allow cold water to enter the heater and exit as hot water.

③Temperature Sensor: Monitors the temperature of the outgoing water.

④Controller: Receives information from the temperature sensor and compares it to the desired temperature.

⑤Set Point: The target temperature of the hot water set by the user or system.

⑥Control Valve: Regulates the gas flow to the burner based on the temperature readings, adjusting the water temperature accordingly.

4.4.4. Safety Features

When designing hot water supply systems, safety is a paramount consideration. As such, designers often incorporate the following measures: Temperature control devices are installed to monitor the temperature of hot water. When the temperature surpasses the predetermined maximum limit, these devices promptly cut off the power supply, ensuring user safety. Pressure control devices are implemented to monitor the pressure of hot water. In instances of excessive pressure, these devices automatically relieve the pressure, safeguarding user safety. Leakage monitoring devices are integrated to swiftly detect any potential leaks. Upon detection, these devices immediately cut off the power supply, mitigating risks to users. Fault detection devices are employed to identify any malfunctions within the water supply system. This proactive measure helps prevent accidents stemming from system failures.

5. CONCLUSION

Through detailed design and optimization, this article provides a comprehensive building services system solution for the E. ON House, covering heating, water supply, drainage, lighting, and control systems. These solutions not only enhance the building's energy efficiency but also align with low-carbon and environmentally sustainable architectural design principles. Future research directions should investigate phase-change material integration in thermal storage and machine learning-enhanced predictive control algorithms. This case study establishes a replicable framework for academic institutions transitioning to low-carbon operations while maintaining functional and aesthetic requirements of building structures.

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