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Information paper – 29
CHP calculations

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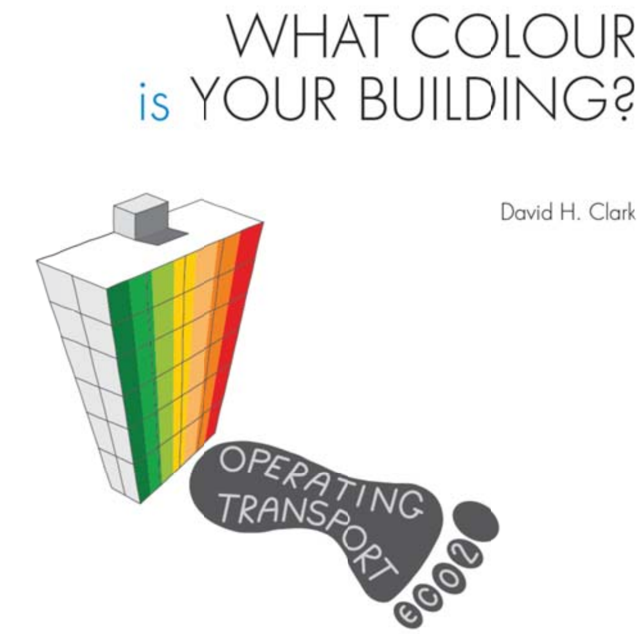
A paper referenced in the book:



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This information paper is one of a series of papers written during the preparation of the book **What Colour is Your Building?** (www.whatcolourisyourbuilding.com). The papers do not form part of the book and have not been peer reviewed. They provide further technical detail, analysis and information to support statements made in the book. All of the papers can be downloaded from www.wholecarbonfootprint.com.

CHP calculations

This information paper describes the two methodologies to estimate the 'best case' performance of CHP systems estimated in the book:

- Figures I.19 and I.20 in Appendix I comparing potential CO_2e savings and costs for buildings with different heat to electricity consumption ratios were based on a simple annual calculation.
- Tables 7.16 and 7.18 in Chapter 7 (and Tables I.39, I.40, I.42 and I.43 in Appendix I) showing preliminary CO2e savings and costs for CHP and trigeneration systems in Building X and Hotel Y were based on a seasonal energy calculation

1. SIMPLE ANNUAL CHP CALCULATION DATA

Methodology

This simple CHP calculation compares the annual electricity and heat consumption to the annual output of the CHP. The methodology is:

- If the annual CHP heat output is less than annual heating consumption then all CHP heat output is utilised and the remaining heat is supplied by a gas boiler.
- If the annual CHP heat output is greater than annual heating consumption then all heating in the building is supplied by the CHP and the excess heat is rejected, (except in trigeneration systems where the heat is converted into chilled water and used to provide cooling, with any excess heat then rejected).

Excess electricity is exported to the grid (which acts like a giant battery storage) and is then reused (imported) when its needed.

Consequently, this calculation methodology gives a 'best possible' scenario for the CO_2e reduction and energy cost savings due to CHP. This is why it is useful as a quick sanity check before undertaking more detailed analysis. If it doesn't stack up using this simple calculation it is unlikely to do so when a more detailed analysis is undertaken.

The variable daily and seasonal heating and cooling demands in a building could result in heat being rejected at certain times of the day, or the CHP not being able to produce enough heat to meet peak demand. To make some allowance for heat rejection during the day, a Heat Utilisation Factor (HUF) has been created by the author. A factor of 100% means no heat is wasted during the year, or that the CHP is able to modulate up and down (from 0% to 100% capacity) without any detrimental impact on performance. The latter is not possible in practice. An option with a HUF of 70% has been calculated to show the impact of not using all the heat efficiently.

Calculations for Figures I.19 and I.20

The total combined electricity and heat energy consumption in the building was set at 100 MWh. For a building with no heating this is all electricity. For a building with a heat to power ratio of 1.5 there is 60 MWh of heat and 40 MWh of electricity. Table 1 shows the assumptions made for buildings where 50% of the annual heating energy consumption is supplied by the CHP and the Heat Utilisation Factor is 70%.

Fuel properties			
(1)	Grid electricity	0.6	$kgCO_2e/kWh$
(2)	Natural gas	0.2	$kgCO_2e/kWh$
(3)	CHP fuel input (gas)	0.2	$kgCO_2e/kWh$
CHP efficiency			
(4)	Electricity output	30%	
(5)	Heating output	45%	
Other equipment			
(6)	Heat rejection	0.15	kW of electricity per 1 kW of heat rejected
(7)	Gas boiler efficiency	90%	
(8)	Heat utilisation factor	70%	100% = no heat wasted, 70% = 30% heat rejected
Heat required from CHP			
(9)	Heat from CHP	50%	The % of the building's heat to be supplied by the CHP

Table 1 **Assumptions for annual CHP calculation with 50% of annual heat from CHP and 30% heat rejected**

Tables 2 and 3 summarise the calculations used. The formulas to calculate the results in Tables 2 and 3 are shown in Table 4.

	Building consumption				Gas CHP inputs & outputs			
A	B	C	D	E	F	G	H	I
Heat to power ratio	Heat	Electricity	CO_2e with no CHP	Heat required from CHP	Input fuel	Heat output	Electricity output	CO_2e from input fuel
0	0	100	**60**	0	0	0	0	0
0.5	33	67	**47**	17	48	22	14	10
1	50	50	**41**	25	72	33	22	14
1.5	**60**	**40**	**37**	**30**	**87**	**39**	**26**	**17**
2	67	33	**35**	33	96	43	29	19
2.5	71	29	**33**	36	103	46	31	21
3	75	25	**32**	38	108	49	33	22
3.5	78	22	**31**	39	112	51	34	22
4	80	20	**30**	40	116	52	35	23
4.5	82	18	**29**	41	118	53	35	24
5	83	17	**29**	42	120	54	36	24

Table 2 **Building consumption and CHP inputs/outputs for different building heat to power ratios with 50% of annual heat from CHP and 30% heat rejected**

A	J	K	L	M	N	P	Q	R	S	T	U
Heat to power ratio	CHP heat used	CHP heat rejected	Electricity to reject heat	Natural gas offset	Net electricity generated	Natural gas to import	Grid electricity to import	Grid electricity to export	CO_2e from imports	**Total CO_2e**	*Reduction in CO_2e*
0	0	0	0.0	0	0	0	100	0	60	**60**	*0%*
0.5	17	5	0.8	19	14	19	53	0	35	**45**	*5%*
1	25	8	1.1	28	21	28	29	0	23	**38**	*8%*
1.5	**30**	**9**	**1.4**	**33**	**25**	**33**	**15**	**0**	**16**	**33**	***11%***
2	33	10	1.5	37	27	37	6	0	11	**30**	*13%*
2.5	36	11	1.6	40	29	40	0	1	7	**28**	*15%*
3	38	11	1.7	42	31	42	0	6	5	**27**	*16%*
3.5	39	12	1.8	43	32	43	0	10	3	**25**	*17%*
4	40	12	1.8	44	33	44	0	13	1	**24**	*18%*
4.5	41	12	1.8	45	34	45	0	15	0	**23**	*19%*
5	42	13	1.9	46	34	46	0	18	-1	**23**	*20%*

Table 3 **Calculation of CO_2e savings due to CHP with 50% of annual heat from CHP and 30% heat rejected**

Annual energy demand of building		Calculation
A	Heat to electricity consumption ratio	
B	Annual heating energy consumption	= 100 x [A / (A=10]
C	Annual electricity energy consumption	= 100 – B
D	CO_2e emissions using natural gas boiler and grid electricity	= [(1) x C] + [(2) x B/(7)]
CHP plant input & output		
E	Heating required from CHP (% of annual consumption)	= B x (9)
F	Input fuel energy (based on heat output)	= G / (5)
G	Annual heat output (to include HUF losses)	= E x [1 + 1–(8)]
H	Annual electrical output	= F x (4)
I	CO_2e emissions from CHP input fuel	= F x (3)
Energy balance calculation		
J	Heat from CHP used in building	= E
K	Heat from CHP to be rejected	= G – J
L	Electricity required to reject surplus heat	= K x (6)
M	Reduction in natural gas to boilers due to CHP	= J / (7)
N	Net electricity generated by CHP	= H - L
P	Natural gas to import for gas boilers	= [B–J] / (7)
Q	Grid electricity to import	= if [C – N] > 0, then [C – N] else 0
R	Excess electricity to export	= if [N – C] > 0, then [N – C] else 0
S	CO_2e due to imported gas for boilers & imported/exported electricity	= [(2) x P] + [(1) x (Q – R)]
T	Total CO_2e in building with CHP	= H + S
U	Percentage reduction in Building CO_2e	= 1 - (T/D)

Table 4 **Formula used in CHP calculations in Tables 2 and 3**

The example above did not consider the use of trigeneration because excess annual heat generation wasn't being considered. However, the methodology can be expanded to include quarterly or monthly energy demand profiles, and adding an absorption chiller to use available heat in the summer when it is not required for heating.

2. SEASONAL CHP CALCULATIONS

A seasonal calculation, using a similar philosophy to the simple annual calculation methodology, but crunching the numbers for heating and cooling energy demand (in kWh) during each season (quarterly) was undertaken to assess CHP in Building X and Hotel Y.

For small CHP systems, providing a base heat load, the factor is assumed to be 95% (i.e. only 5% of heat is rejected due to hourly variations in heat demand). For larger systems, providing in excess of the base heat load, a factor of 90% is assumed.

Example screen shots are provided for:

- Base load gas CHP (100 kWe) in Hotel Y – refer to Figure 1.
- Biofuel trigeneration (250 kWe) on Building X – refer to Figure 2.

CHP - Preliminary Analysis

CHP Efficiency

Fuel Source	Nat Gas
% electrical output	30%
% heat output	45%
% losses	25%
Heat to power ratio	*1.5*
Min operating capacity:	100%
Heat utilisation factor:	95%

Energy Demand (per m2)

	Quarterly Energy				Annual
	Spring	Summer	Autumn	Winter	Thermal
Heating (kWh-heat)	44	17	44	98	203
Cooling (kWh-cooling)	20	60	20	0	100
Electricity for cooling (kWhe)	*4*	*12*	*4*	*0*	*20*
Electricity (excl. cooling)	20	20	20	20	80
Total Electricity (kWhe)	24	32	24	20	100

Size of CHP (kWe)

		kWe/m2
Option 1	100	*0.010*
Option 2	250	*0.025*
Option 3	300	*0.030*
Operating Hours / year	5,000	
Area of building (m2)	10,000	
Cost of CHP (per kWe)	£2,400	

Cooling / Heating Efficiencies

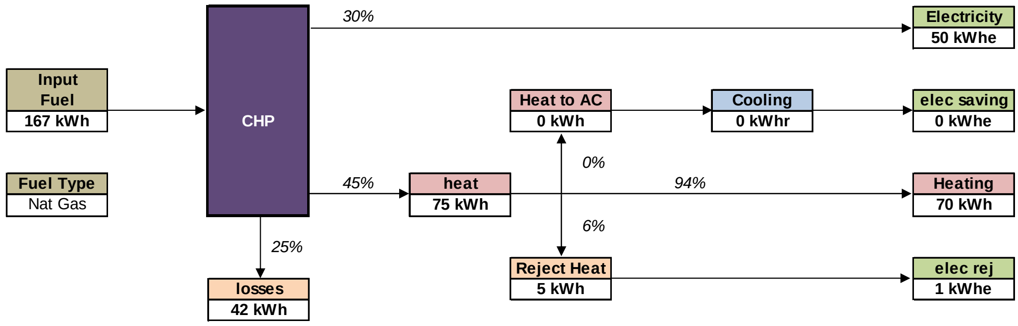
Absorption Chiller COP	0.7
Electric Chiller CoP	5.0
Gas Boiler	90%
Heat Rejection	0.15
kWe per KW heat rejected from CHP	
Cost of abs chiller	£100,000

Fuel Factors

	kgCO2/kWh	£/kWh
Grid electricity	0.600	£0.100
Natural Gas	0.200	£0.035
CHP fuel: Nat Gas	0.200	£0.035
Export electricity		£0.030

Sizing of system:	5) Option 1 = 100 kWe (111% of base heat)
Absorption Chiller:	No
Modulate to suit heat demand:	No (Constant 100%)
Daily heat utilisation factor:	95%

Total CO2e (CHP + Imports):	93	
Net CO2 saving (kgCO2):	11.9	*11%*
Saving in fuel costs:	£1.83	*10%*
Indicative payback:	13	



Base Case - Gas & Grid

	kWh	kgCO2	Cost
Electricity	100	60	£10.00
Gas	225	45	£7.88
Total	**325**	**105**	**£17.88**

Net Electricity from CHP:	49 kWhe	*49%*
System efficiency:	72%	
% of annual heat supplied:	35%	
Grid electricity required:	51 kWhe	
Net electricity exported:	0 kWhe	
Additional gas required:	147 kWh	
Capital Cost:	£240,000	

Fig 1 **Screen shot of seasonal calculation for gas CHP (250kWe) in Building X**

CHP - Preliminary Analysis

CHP Efficiency

Fuel Source	Biofuel
% electrical output	30%
% heat output	45%
% losses	25%
Heat to power ratio	*1.5*
Min operating capacity:	100%
Heat utilisation factor:	90%

Energy Demand (per m2)	Quarterly Energy				Annual
	Spring	Summer	Autumn	Winter	Thermal
Heating (kWh-heat)	16	1	14	36	67.5
Cooling (kWh-cooling)	20	50	20	10	100
Electricity for cooling (kWhe)	*4*	*10*	*4*	*2*	*20*
Electricity (excl. cooling)	33	33	33	33	130
Total Electricity (kWhe)	37	43	37	35	150

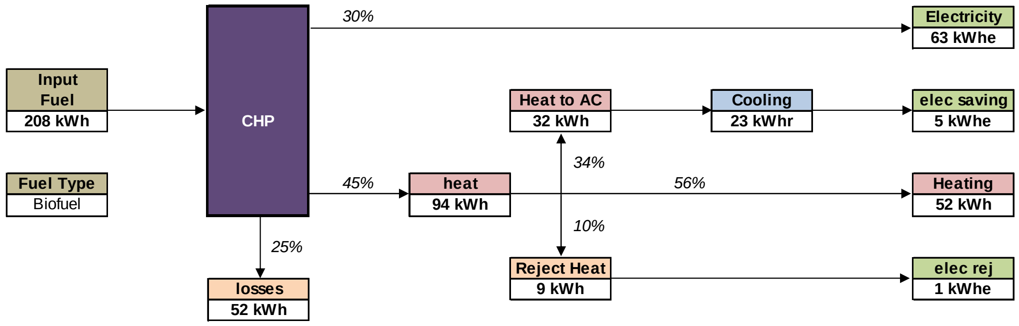
Size of CHP (kWe)		*kWe/m2*
Option 1	10	*0.001*
Option 2	100	*0.010*
Option 3	250	*0.025*
Operating Hours / year	2,500	
Area of building (m2)	10,000	
Cost of CHP (per kWe)	£2,400	

Cooling / Heating Efficiencies	
Absorption Chiller COP	0.7
Electric Chiller CoP	5.0
Gas Boiler	90%
Heat Rejection	0.15
kWe per KW heat rejected from CHP	
Cost of abs chiller	£100,000

Fuel Factors	kgCO2/kWh	£/kWh
Grid electricity	0.600	£0.100
Natural Gas	0.200	£0.035
CHP fuel: Biofuel	0.120	£0.070
Export electricity		£0.030

Sizing of system:	7) Option 3 = 250 kWe (2131% of base heat)
Absorption Chiller:	Yes
Modulate to suit heat demand:	No (Constant 100%)
Daily heat utilisation factor:	90%

Total CO2e (CHP + Imports):	79	
Net CO2 saving (kgCO2):	26.0	*25%*
Saving in fuel costs:	-£5.99	*-34%*
Indicative payback:	no payback	



Base Case - Gas & Grid

	kWh	kgCO2	Cost
Electricity	150	90	£15.00
Gas	75	15	£2.63
Total	225	105	£17.63

Net Electricity from CHP:	66 kWhe	*44%*
System efficiency:	70%	
% of annual heat supplied:	77%	
Grid electricity required:	84 kWhe	
Net electricity exported:	0 kWhe	
Additional gas required:	17 kWh	
Capital Cost:	£700,000	

Fig 2 Screen shot of seasonal calculation for biofuel trigeneration (250kWe) in Building X

The inevitable legal bit