CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761120

Carbon Emissions Efficiency and Economics of Combined Heat and Power in New Zealand

Martin J. Atkins[a,*], Timothy G. Walmsley[b], Matthias Philipp[c], Michael R. W. Walmsley[a], James R. Neale[a]

[a]Energy Research Centre, School of Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand
[b]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
[c]Technische Hochschule Ingolstadt, Insitute of new Energy Systems, Esplanade 10 85049 Ingolstadt, Germany
martin.atkins@waikato.ac.nz

Combined Heat and Power (CHP) or cogeneration, is a common and often cost effective method to maximise the efficiency and utilisation of fossil fuels. Greenhouse Gas (GHG) emissions from the electricity generated using CHP is also an important factor to consider, especially within the framework of emissions reduction and uptake of renewable generation. This paper will present a detailed analysis of the economics of industrial CHP within New Zealand and examine the potential of CHP to contribute to GHG emissions reduction. An emissions factor from electricity generation using CHP is defined based on the marginal efficiency of electricity generation. The economics of CHP in New Zealand can be favourable under certain conditions although the emissions of generation using fossil fuels in all cases was higher than grid purchased electricity, due to high levels of renewable generation. A reduction in emissions can occur in countries that have medium to high Grid Emissions Factors (GEF) such as the US, UK, Australia, India, and China. Countries with GEF less than around 0.2 $t_{CO2\text{-}eq}/MW_{el}$ would need to utilise biomass to achieve large emissions reductions using CHP.

1. Introduction

Decarbonising industrial energy and electricity generation systems and is an important but difficult task of climate change mitigation. Combined Heat and Power (CHP) or cogeneration is an important industrial practice to maximise the efficiency and utilisation of fossil fuels. As the name suggests both process heat and power are generated together resulting in a higher efficiency compared to generating heat and power separately using the same fuel. Another benefit often cited is a reduction in Greenhouse Gas (GHG) emissions from the use of CHP (Schumm et al., 2016). Although it is well established that fuel efficiency is improved, the change in GHG emissions is more difficult to determine and is dependent on the location, type of CHP plant and the source of alternate electricity supply (Philipp et al., 2016).
Several countries and regions, such as the USA (Brown et al., 2013) and the European Union (Directive, 2004), have targeted policies aimed at the promotion of CHP in industrial applications for both efficiency improvements, primary energy and emissions reduction; however effectiveness of these policies has been questioned (Moya, 2013). In countries that have a low Grid Emissions Factor (GEF) the expanded use of CHP using fossil fuel can potentially increase the overall emissions from electricity by displacing renewable or low carbon generation sources (Keen and Apt, 2016). The net benefit for emissions reductions from using CHP is dependent on several factors including fuel type, overall grid emissions factor, grid based generation displaced by CHP (if any), and efficiency of CHP generation.
The economics of industrial CHP is largely dependent on two main factors, the site fuel to power cost ratio and the capital cost of the CHP system (Comodi and Rossi, 2016). In countries that have a high degree of thermal power generation, fossil fuel and electricity costs tend to be coupled (if subsidies are disregarded), whereas in countries that have a high degree of renewable electricity generation, electricity costs can be decoupled from fuel prices further effecting the economics of CHP. Subsidies or rebates may be available due to aggressive

Please cite this article as: Atkins M.J., Walmsley T.G., Philipp M., Walmsley M.R.W., Neale J.R., 2017, Carbon emissions efficiency and economics of combined heat and power in new zealand, Chemical Engineering Transactions, 61, 733-738 DOI:10.3303/CET1761120

policy instruments, which may assist the economics, although these may be dependent on the type and performance of the system (Directive, 2004).
The aim of this paper is to determine the emissions reduction potential for New Zealand compared to Germany, United Kingdom, France, Finland and Australia, as well as the economics for industrial CHP in New Zealand. CHP technology will be limited to the use of back pressure and condensing steam turbines and gas turbines with heat recovery steam generators (HRSG). Net emissions from CHP electricity generation will be compared to grid based generation in other developed and developing nations to demonstrate under what conditions CHP using fossil fuels increases or decreases carbon emissions. An example case study is presented.

1.1 Electricity Generation and CHP in New Zealand

Electricity in New Zealand is mostly generated using renewable sources (Walmsley et al., 2014), and the national target is to achieve 90 % or more renewables by 2025. In 2016, 84 % of generation came from renewable sources (hydro 60 %, geothermal 18 %, wind 5 %) and 16 % from fossil fuels (gas 13 %, coal 3 %). These levels are predicted to increase over the coming years to over 90 % as the remaining coal generation is retired and additional geothermal and wind are constructed. New Zealand has an extremely liberal electricity market with no subsidies or incentives for using renewables. The lowest Long Run Marginal Cost (LRMC) of new generation is for geothermal and wind being between NZ$80 and NZ$100/MWh$_{el}$ (MBIE, 2016). In 2015 the average industrial power price for large users was approximately NZ$80/MWh$_{el}$. Indicative fuel cost in New Zealand are given in Table 1.
There is approximately 562 MW$_{el}$ of installed CHP plant. The applications include (from largest installed capacity) from steel, dairy processing, pulp & paper, wood processing, hospitals, and other sectors. A wide range of energy sources are used including gas, coal, wood, geothermal, waste heat and biogas. There has been very little growth in CHP plants over the past 20 y, neither have there been dedicated policies to promote or incentivise CHP in New Zealand. GHG emissions are priced under the Emissions Trading Scheme (ETS), a market based mechanism. Under the scheme, emitters are required to surrender units purchased on the market to cover their emissions liability resulting from fuel combustion and the like. As of March 2017 the current trading price was around NZ$18/t of CO_2 equivalent.

2. CHP Efficiency, Emissions Reduction, and Marginal Efficiency of Generation

CHP efficiency (η_{CHP}) is defined as the sum of work or power (W_{CHP}) and heat produced (Q_{CHP}) using CHP over the total fuel consumption ($Q_{f,CHP}$) as in Eq(1a). It is common to define an electrical efficiency (η_{el}) and thermal efficiency (η_{th}) of CHP as in Eq(1b) and Eq(1c).

$$\eta_{CHP} = \frac{W_{CHP} + Q_{CHP}}{Q_{f,CHP}} = \eta_{el} + \eta_{th} \tag{1a}$$

$$\eta_{el} = \frac{W_{CHP}}{Q_{f,CHP}} \tag{1b}$$

$$\eta_{th} = \frac{Q_{CHP}}{Q_{f,CHP}} \tag{1c}$$

A marginal efficiency of electricity generation ($\eta_{el,marginal}$) can be defined as the amount of power generated over the additional fuel required for electricity generation (ΔQ_f) as in Eq(2). ΔQ_f is defined in Eq(3) as the difference between the total fuel used in CHP mode compared to the fuel used in the reference case ($Q_{f,ref}$). The fuel use for the base case here is defined as the fuel to provide only the thermal requirement only using a boiler operating at the typical efficiency for that boiler and fuel type.

$$\eta_{el,marginal} = \frac{\Delta W_{CHP}}{\Delta Q_f} \tag{2}$$

$$\Delta Q_f = Q_{f,CHP} - Q_{f,ref} \tag{3}$$

The emissions from the electricity generation from CHP ($\varepsilon_{el,CHP}$) can then be calculated using the fuel emissions factor (ε_f) by the marginal efficiency of electricity generation as in Eq(4). Fuel emissions factors for several typical fuels are given in Table 1.

$$\varepsilon_{el,CHP} = \left[\frac{\varepsilon_f}{\eta_{el,marginal}}\right] \tag{4}$$

Table 1: GHG emissions factors indicative fuel costs for New Zealand.

Fuel	Fuel Emissions Factor (ε_f) [$t_{CO2\text{-}eq}$/GJ_f]	Fuel Cost Range[a] [NZ$/$GJ_f$]
Biomass – Forest Residues (BM)	0.0020	7.00 – 15.00
Natural Gas (NG)	0.0531	7.00 – 16.00
Coal – Lignite (CL)	0.1000	3.50 – 8.00
Coal – Sub-bituminous (CSB)	0.0953	7.50 – 12.00

[a] includes any transport and distribution costs

The Grid Emissions Factor (GEF) (ε_{GEF}) is defined as the average GHG emissions from the transmission grid based on a fixed geographic region (usually a country or region) and dependant on the generation mix. There will be a net reduction in GHG emissions if $\varepsilon_{el,CHP}$ is less than the GEF and vice versa. The GEF for several countries is shown in Table 2.

Table 2: Grid Emissions Factors for a range of countries for 2013.

Country	Grid Emissions Factor (ε_{GEf}) [$t_{CO2\text{-}eq}$/MWh_{el}]	Country	Grid Emissions Factor (ε_{GEf}) [$t_{CO2\text{-}eq}$/MWh_{el}]
New Zealand (NZ)	0.155	China (CN)	0.807
Australia (AU)	0.798	India (IN)	0.792
France (FR)	0.076	Japan (JP)	0.572
Germany (GE)	0.546	Malaysia (MY)	0.693
United Kingdom (UK)	0.476	Canada (CA)	0.161
Finland (FI)	0.311	United States (US)	0.497

A common measure used to express the effectiveness of CHP is the Primary Energy Savings (PES), as in Eq(5) where $\eta_{el,ref}$ and $\eta_{th,ref}$ is the electrical and thermal efficiency of separate stand-alone plants. PES quantifies the reduction in primary energy for producing heat and power using CHP compared to separate plants (Badami et al., 2014). The core assumption of the PES is that CHP generation displaces existing or new thermal generation. In countries with high levels of renewable or nuclear generation this may not be the case, and CHP may displace low emission sources. In countries such as New Zealand, CHP would displace new renewables generation and so the PES is not a good measure of effectiveness. To measure the GHG emissions reduction a percentage reduction per unit of power generated (β) using CHP can also be calculated using Eq(6).

$$PES = 1 - \frac{1}{\frac{\eta_{el}}{\eta_{el,ref}} + \frac{\eta_{th}}{\eta_{th,ref}}} \tag{5}$$

$$\beta = \left[\frac{\varepsilon_{GEF} - \varepsilon_{el,CHP}}{\varepsilon_{GEF}}\right] \tag{6}$$

The $\varepsilon_{el,CHP}$ for a range of fuels as a function of $\eta_{el,marginal}$ is shown in Figure 1a. For fossil fuels $\varepsilon_{el,CHP}$ is highly dependent on $\eta_{el,marginal}$, however biomass was less effected due to the very low emissions factor. The percentage reduction in emissions as a function of GEF is shown in Figure 1b for two different marginal efficiencies. For some countries, such as New Zealand, Canada, and France, fossil fuels always increase emissions and biomass based CHP is the only viable option for emissions reductions via CHP. For countries with medium GEF, such as Germany, UK, US, Finland, and Japan reductions can be achieved if high $\eta_{el,marginal}$ are achieved using natural gas. This would exclude the use of gas turbines with HRSG due to the relatively low $\eta_{el,marginal}$ (<35 %). In countries with high GEF, such as China, Australia, and India, both coal and natural gas CHP yield significant reductions.

3. Economics of CHP

A measure that is often used as an indicator of the economic performance of CHP systems is the Cost Saving Ratio (CSR) (Comodi and Rossi, 2016), as defined in Eq(7), where C_{base} is the energy cost of the base case with no CHP and C_{CHP} is the energy cost of CHP. One of the deficiencies of the measure is it fails to include capital and operational cost of the additional equipment over the base case (e.g. turbine, generator etc.). A better measure is to calculate a discounted levelised cost in real terms (Heck et al., 2016) of power generation and compare that to the cost of power purchased from the national grid. As a first order comparison the average power price can be used, although for markets with dynamic pricing a more detailed analysis would be needed.

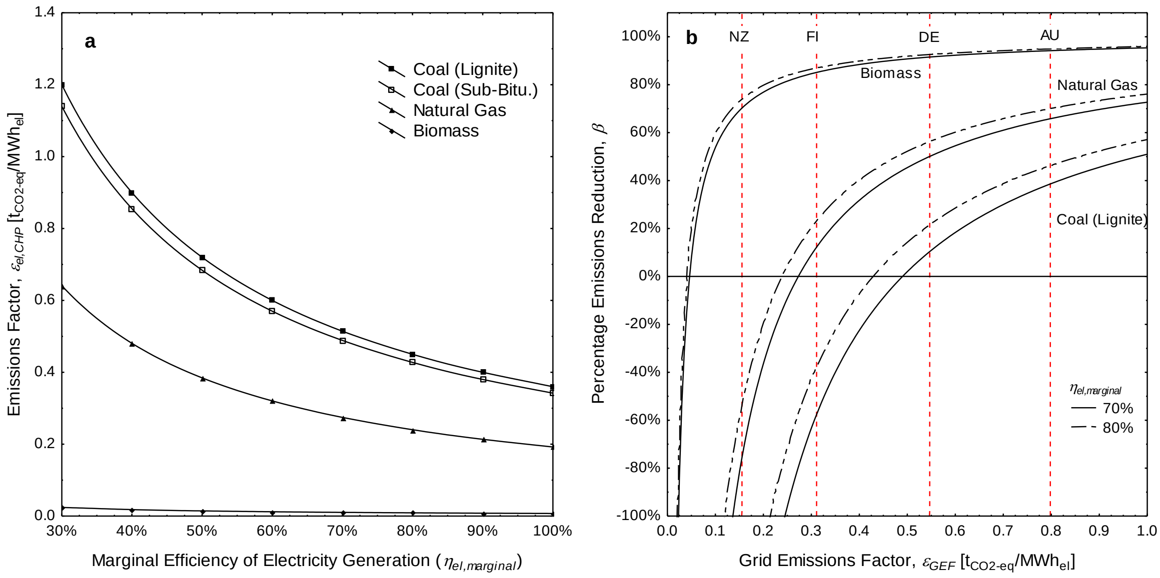

Figure 1: Emissions factor for CHP power generation (a) and percentage emissions reduction per unit of power generated using CHP (b).

$$CSR = \left[\frac{C_{base} - C_{CHP}}{C_{base}}\right] \tag{7}$$

The capital cost function of a back pressure steam turbine (CC_{ST}) and gas turbine (CC_{GT}), including generator, installation and balance of plant, is given in Eq(8) and Eq(9).

$$CC_{ST} = 1077W_{CHP} \tag{8}$$

$$CC_{GT} = 2500{W_{CHP}}^{-0.273} \tag{9}$$

Based on local experience, non-fuel operation and maintenance (O&M) costs were assumed to be NZ$7.50/$MWh_{el}$ and NZ$10/$MWh_{el}$ for the steam turbine and gas turbine. A levelised cost of generation was calculated, including depreciation of capital equipment under NZ's tax regime. The straight-line depreciation rate used is 7 %/y and the corporate tax rate 28 %. A discount rate of 5 % is used and a 5 % per year cost escalation for both fuel, carbon and O&M are assumed.
The levelised cost of CHP generation is shown in Figure 2. For steam turbines (Figure 2a) the levelised cost is lower than the average industrial price for a range of fuel prices and marginal efficiencies. It should be noted that the difference in cost between the different fuels is exclusively due to the difference carbon costs. The use of a gas turbine for CHP in NZ (Figure 2b) is uneconomic due to the high capital cost (compared to a steam turbine), O&M costs and inherent low $\eta_{el,marginal}$.

4. Example CHP System

An example of a typical CHP system is shown in Figure 3, illustrating a two-stage back pressure steam turbine reducing process steam from the High-Pressure header (40 bar_g) to a Low Pressure (10 bar_g) header. The system has been modelled in PetroSim 6.1. Condensate return and the deaerator is also shown. The option for pressure reduction values instead of the steam turbine is also shown, using feedwater as the desuperheater water. The performance parameters of the system is shown in Table 3. The total fuel used increased in CHP mode but the total cost of fuel, power and carbon is considered decreased by NZ$1.3M (8.6 %) due to the lower electricity cost. The total emissions for electricity increased when using natural gas (β=-59 %) and lignite (β=-197 %), but reduced for biomass (β=94 %).

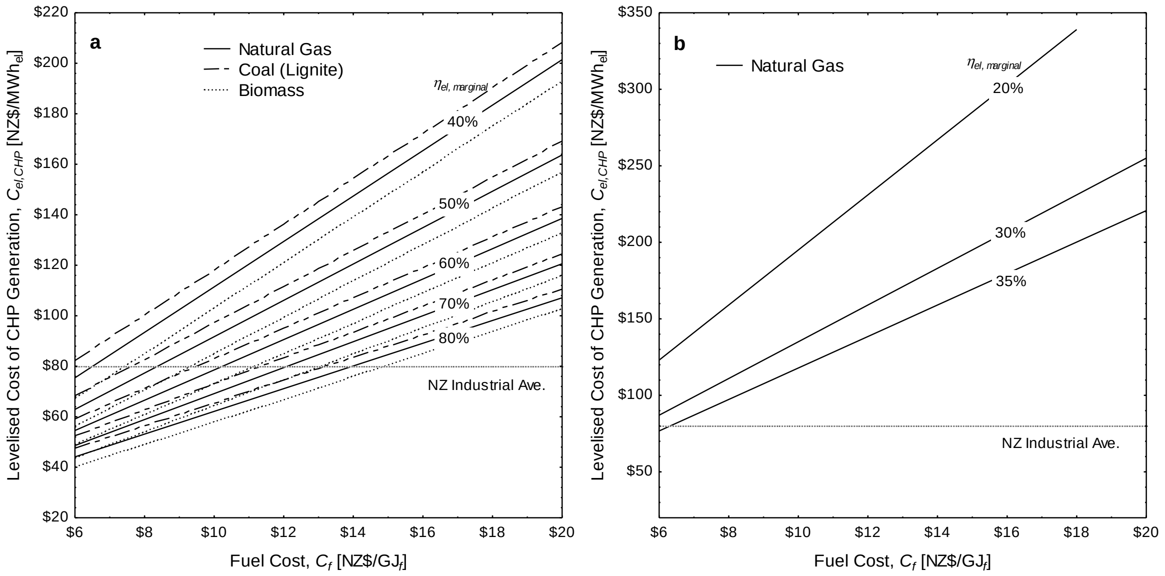

Figure 2: Levelised cost of power generation using back pressure steam turbines (a) and gas turbine (b) at different efficiency of electricity generation. A carbon price of NZ\$18/t$_{CO2-eq}$ is included.

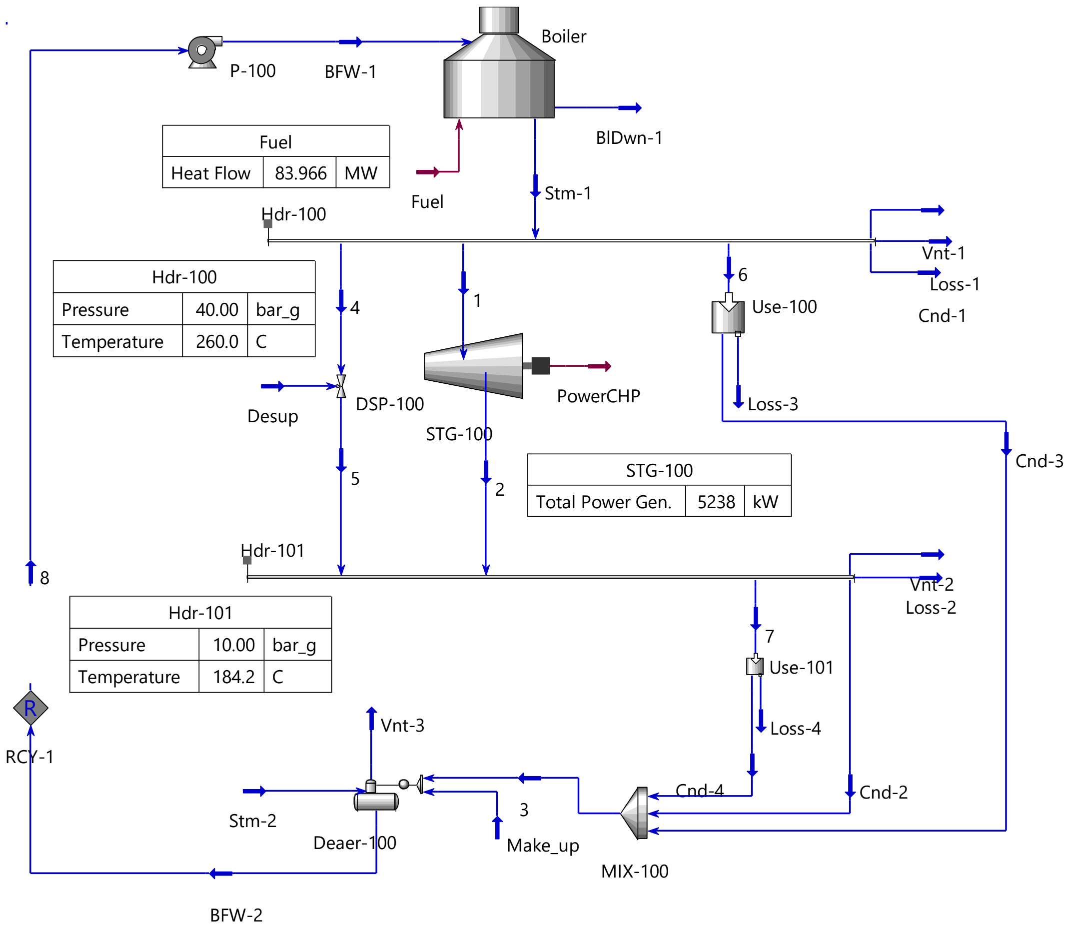

Figure 3: A typical example of a multi stage back pressure steam in use for CHP.

Table 3: Performance Parameters of Case Study.

Parameter	Base Case	CHP
$Q_{f,CHP}$ [MW]	77.27	83.97
W_{CHP} [MW_{el}]	-	5.24
Q_{CHP} [MW_{th}]	64.89	64.89
η_{el}, η_{th}	-, 84 %	6.2 %, 77.3 %
η_{CHP}	-	83.5 %
$\eta_{el,marginal}$	-	78.3 %
$\varepsilon_{el,CHP}$ [t_{CO2-eq}/MWh_{el}]	-	0.247 (NG), 0.460 (CL), 0.009 (BM)
Electricity Cost [NZ$/$MWh_{el}$]	80.00	51.66[a]
Annual Fuel + Power + Carbon Cost [NZ$/y][b]	15.79M	14.43 M
Electricity Emissions [t_{CO2-eq}/y]	4872 (Grid)	7,764 (NG), 14,460 (CL), 283 (BM)

[a] levelised cost per MWh_{el}, NG at $7/GJ, carbon emissions price at $18/$t_{CO2-eq}$

[b] based on 6,000 h/y, NG at $7/GJ, carbon emissions price at $18/$t_{CO2-eq}$, excludes capital cost

5. Conclusions

Although in many cases there is a sensible economic rationale to utilise CHP in NZ (based on levelised cost of generation), the emissions factor for fossil fuels is greater than the grid emissions factor. Aany use of CHP involving fossil fuels will actually increase emissions. Based on NZ's future demand and generation scenarios further fossil fuel CHP would not displace thermal/fossil fuel generation and only displace low-emissions renewable generation. For other countries with higher grid emissions factors the fuel type and marginal efficiency of generation need to be known to determine the emissions reduction potential of CHP.

Acknowledgements

This research has been supported by the project "Catalyzing Investment in New Zealand Wood-Energy Industrial Symbiosis Opportunities" funded by the New Zealand Ministry of Business, Innovation, and Employment, and the EU project "Sustainable Process Integration Laboratory – SPIL", project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by EU "CZ Operational Programme Research, Development and Education", Priority 1: Strengthening capacity for quality research.

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